ARPA Network Information Center

Stanford Research Institute
333 Ravenswood Avenue
Menlo Park, California 94025

Packet Radio Temporary Note #164

PERFORMANCE EVALUATION OF PACKET RADIO SYSTEMS

January 8, 1976

NETWORK ANALYSIS CORPORATION
Beechwood, Old Tappan Road
Glen Cove, New York 11542

PERFORMANCE EVALUATION OF PACKET RADIO SYSTEMS

1. INTRODUCTION

The performance of the packet radio network can be improved by software means (e.g., improved routing and communication protocols) or by hardware means (e.g., increasing the channel capacity in the repeater-station network or improving the capture of receivers). A quantitative demonstration of the increase in system capacity and/or the reduction in the delay for each specific improvement, enables more objective decision making regarding the means one should choose. It is not the objective of this report to establish absolute values of performance for the various system modifications considered. Rather, the objective is to evaluate specific hardware and software design alternatives. The various modifications are compared on the basis of relative performance obtained by simulation. The basic elements which define the system simulated and the criteria used for comparison are presented in Section 2.

One of the characteristics of the packet radio network is that packets which cannot be delivered within an assigned amount of resources are discarded. This prevents lockups resulting from the unavailability of repeater buffers on the one hand, and, on the other hand, it reduces the possibility of local traffic instability when random access schemes are used. Furthermore, there seems to be no rationale in keeping the packet in the network for a long period of time since another copy of same will be introduced via the mechanism of end-to-end retransmission; the latter ends up competing with the former for network resources. The Maximum Number of Transmissions (MNT) per hop is a measure of the amount of resources assigned to a packet for traversing in the radio network. In Section 3 we compare network performance as a function of MNT and recommend MNT values for practical networks [NAC, 75a].

In Section 4 we compare the performance of the packet radio system with Zero Capture receivers against a system with Perfect Capture receivers. The objective is to determine whether improved reception characteristics will significantly improve system performance and to identify other properties resulting from improved reception [NAC, 75b].

An alternative way to improve reception is by using a checksum at the end of the packet header in addition to that used at the end of the packet. The advantage gained by using the header checksum is by being able to utilize the header information in cases in which the portion of the header is correctly received whereas the whole packet is received in error. The Hop-by-Hop Acknowledgment (HBH Ack) scheme in the packet radio system is based on the correct reception of a packet which is already stored in the receiving device, when the packet was transmitted by a device closer to the destination. Hence, in cases in which it is a packet with text, there is a higher probability for correctly receiving the header section than the probability of correctly receiving the entire packet. This is true in systems which use non-slotted ALOHA [Abramson, 70] or carrier-sense multiple access [Kleinrock, 75] schemes. The performance of packet radio systems with and without a checksum at the end of the header are compared in Section 5.

It has been demonstrated [Frank, 75] that a system with two data rate channels, a low data rate for communication between terminals and repeaters (or stations) and a high data rate for communication in the repeater-station network, performs significantly better than a system with a single data rate channel. One of the hardware design alternatives is to determine a proper value for the high data rate, for a given low data rate channel. In Section 6 we attempt to answer this question by studying the performance of the packet radio network as a function of the ratio of the high to low data rate channels.

2. DEFINITION OF THE SYSTEM AND PERFORMANCE MEASURES

A detailed description of the system simulated is given in [NAC, 74]. The basic elements which define the system studied are stated below:

. Common channel two data rates. A low data rate for communication between a terminal and a repeater (or station), and a high data rate in the repeater - station network. A packet on the high data rate channel can interfere with a packet on the low data rate channel, and vice versa.

. The topology consisted of 1 station and 48 repeaters. The connectivity was moderate, which resulted in a network of many hops (up to 7). The location of repeaters and stations and the radio connectivity are shown in Figure 1. Terminals are introduced at random times and are placed in random locations in the plane "covered" by repeaters and stations. A terminal performs a short interaction of sending and receiving a few packets and then departs from the system. The rate at which terminals are introduced and the amount of communication depend on the traffic offered to the system and are controlled by parameters.

. The routing was hierarchical with restricted alternate routing; the alternate routing enables only forward transmission of a packet bypassing only one failed or busy repeater, before returning to the established path [Gitman, 75]. The radio links assigned for routing form a tree structure. Figure 2 shows the structure of the network studied.

. The channel access scheme is non-persistent, non-slotted, carrier sense [Kleinrock, 75].

Digitized by the Internet Archive
in 2025 with funding from
Amateur Radio Digital Communications, Grant 151

https://archive.org/details/temporary-note-164

- Other parameters used in these experiments are: A maximum of 3 end-to-end transmissions and a timeout of 60 slots (packet transmission time on low data rate) between end-to-end transmissions.

The following are the performance measures used for system evaluation and comparison:

- System throughput/system input rate. The throughput includes the acknowleged information packets. Hence, the above ratio is a lower bound on network performance.

- Percentage of total loss. The loss includes packets of terminals which are blocked and packets which are not delivered to the destination after the maximum number of end-to-end transmissions.

- Delays. The round trip delay averaged over all packets, independent of the number of hops from the station was used.

- Average buffer occupancy. The average number of occupied buffers in the entire repeater network is another measure used to compare the systems. More information about buffer occupancy is shown in the form of the number of packets as a function of time.

The time scale used in this report is the transmission time of an information packet on the low data rate channel, or a slot. If it is assumed that the size of an information packet is 2,000 bits and the low data rate channel is 100 Kbps, a slot time would be 20 msec. The size of short packets (ETE ack, search, response to search) used in the simulation is 10% of an information packet. Similarly, the traffic rates are in percentages of the low data rate channel; thus, a throughput of 30% means a throughput of 30 Kbps of bits in information packets.

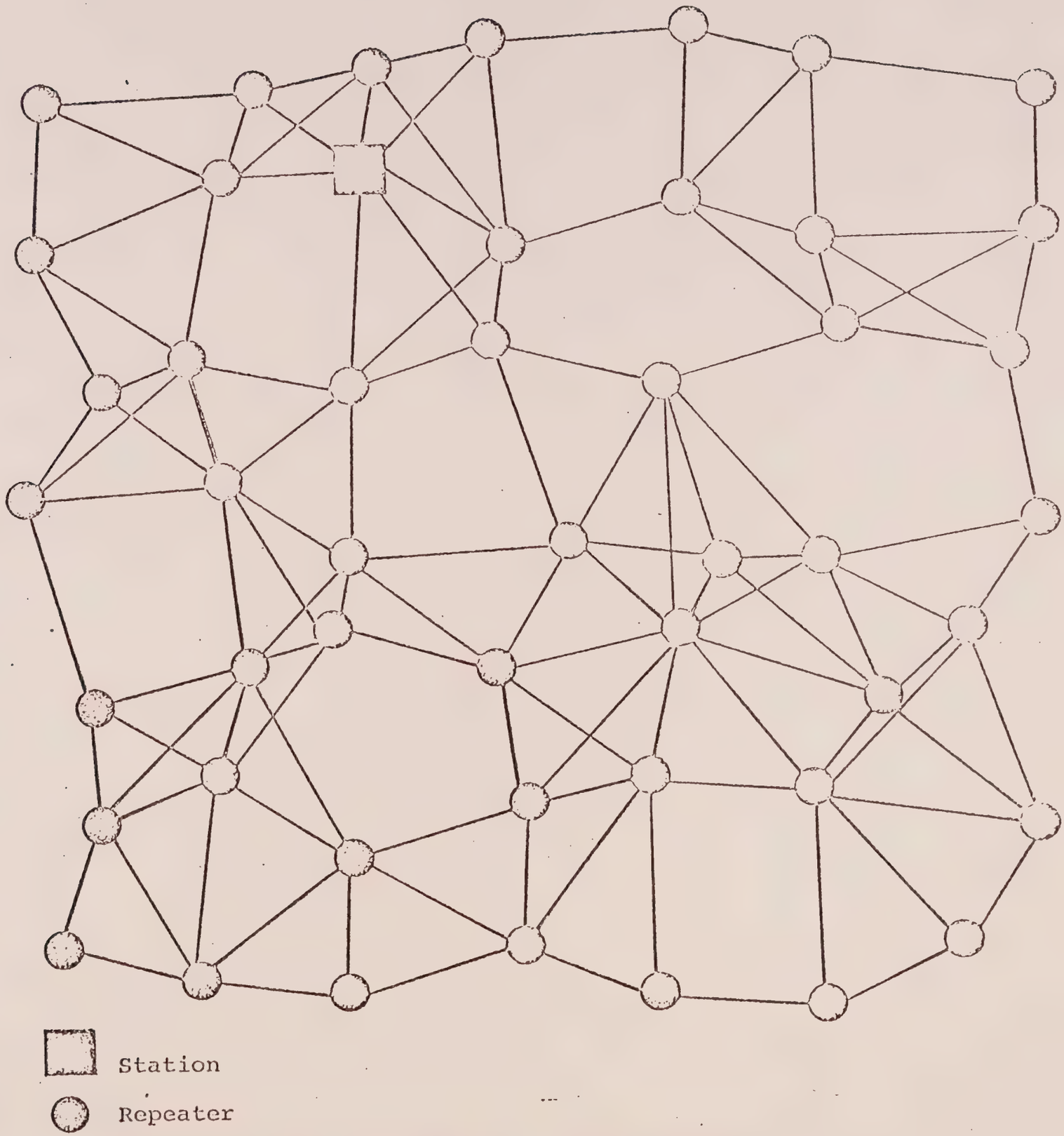


FIGURE 1: RADIO CONNECTIVITY OF REPEATERS & STATIONS

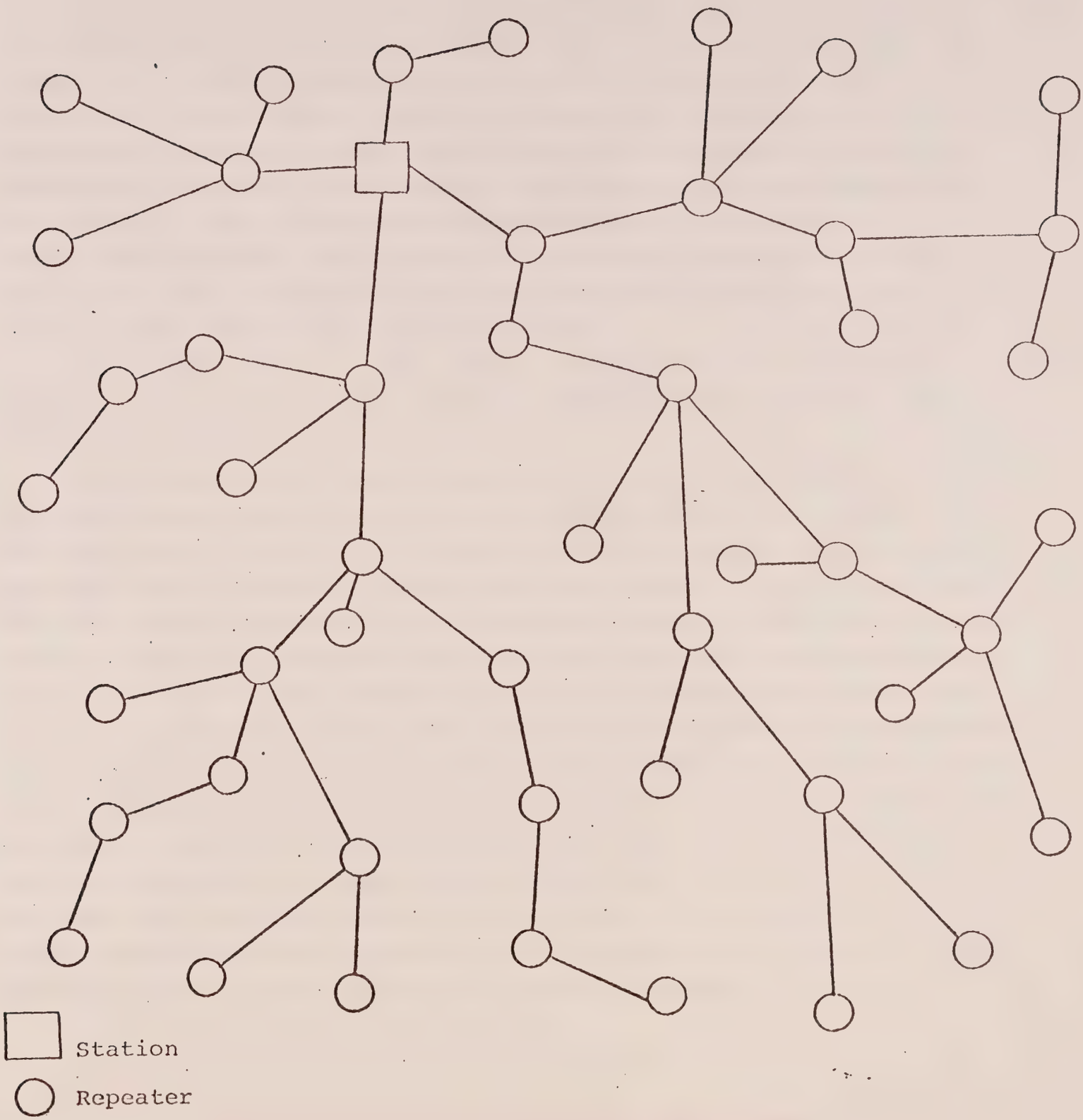


FIGURE 2: TREE STRUCTURE OF RADIO LINKS ASSIGNED FOR ROUTING

3. MAXIMUM NUMBER OF TRANSMISSIONS FOR REPEATERS AND STATIONS

In this section we report on a study for evaluating network performance as a function of the amount of resources assigned to a packet. In the present implementation of the packet radio network, the only parameter which determines the resources allocated to a packet per end-to-end transmission is the Maximum Number of Transmissions (MNT) per hop that a device uses before discarding the packet. This is because the routing has the property of being shortest path, the alternate routing is restricted (thus one cannot limit the number of hops), and the packet does not carry a time stamp which can be limited.

The system used for the study is that defined in Section 2, with a 4 to 1 ratio of data rates, a zero capture receiver, and a header checksum.

In the study, all system parameters were kept constant and the performance was studied as a function of MNT. The values of MNT used were: 3, 6, 9, 15, ∞, and a variable number which was a function of the number of hops from the station. For the variable MNT the formula used was 10 - (Hierarchy Level). Thus, the station used an MNT of 9, repeaters one hop away from the station used the value of 8, etc. The reason for this variable MNT assignment are theoretical results showing that the average number of transmissions before success increases with the traffic level, and previous simulation results and analysis which demonstrated that the traffic bottleneck is near the station and that the traffic level decreases with the distance (in hops) from the station. The value of infinity (∞) was used as a reference value. It also simulates the case in which packets are not discarded until successfully forwarded, as is done is point-to-point store and forward networks.

For each value of MNT, the system was run with two values of offered rate: 15% and 30%. The number of terminals simulated for the various tests ranged from 50 to 100. The average number of hops of the terminals from the station (measured) was 4 to 4.5.

Table 1 summarizes the performance of all the simulation runs. One can see that all the systems, apart from that with MNT = ∞, perform well when the offered rate is 15%. The unsatisfactory performance of the system with MNT = ∞ can also be seen in Figure 3, where the throughput and buffer occupancy are shown as a function of time. Although one can observe the same qualitative differences for the 15% offered rate as the ones for 30% offered rates, the absolute differences in performance seem to be too small to justify conclusions. Hence, the runs with 30% offered rate are used for comparison.

Figures 4, 5, and 6 compare the various systems in terms of performance measures defined in Section 2, as a function of MNT.

The comparison of the system for all values of MNT demonstrates that the variable MNT scheme shows much better performance in all measures used. There is a large difference in performance between the variable MNT and any of the fixed MNT cases. For example, the average round-trip delay for the variable MNT case is 17.04 slots whereas for other cases it is 34.12, 33.8, 39.0, 34.12, and 29.75, for MNT = 3, 6, 9, 15, and ∞, respectively. Figures 7 through 9 show the throughput and buffer occupancy as a function of time for the 30% offered rate. These Figures immediately reveal the difference in performance.

The comparison of systems with MNT of 3 or 6 against systems with MNT of 9 or 15, shows that the former perform better. The only measure in which the system with MNT of 15 is better than

that with MNT of 3 is the average round trip packet delay per hop (8.12 vs. 8.66); however, this is obtained for a lower throughput (22.91% vs. 27.75%, respectively). In all other measures drawn in Figures 4 through 6 the performance of MNT of 3 or 6 is better than that of MNT 9 or 15.

In comparing MNT of 3 and 6, neither case is uniformly better than the other. The system with MNT of 3 shows better performance in the ratio of throughput to input rate; whereas that with MNT of 6 shows better performance in delay.

It is somewhat surprising that the system with MNT of 15 performs generally better than that with MNT of 9. However, the difference in performance is small; furthermore, the comparison is reversed in favor of the system with MNT of 9 for the runs with 15% offered rate.

As a final note, it is pointed out that the maximum throughput obtained in these experiments is higher than what was previously obtained with the same network topology and zero capture receivers. In previous experiments [Frank, 75] a throughput of 27.5% was obtained when the ratio of data rates was 5 to 1. The performance obtained in this series of experiments with the variable MNT is 29.12% throughput at the relatively low average round trip delay of 17.04 slots (approximately 340 milliseconds at 100 kilobits per second and 2,000 bit packets). Other performance measures such as the total loss and the buffer occupancy are also very good, this can be seen in Table 1 and Figure 9. This implies that the capacity of a single station packet radio network can be increased above 30% when protocols are improved and the delay requirements are relaxed.

	MAXIMUM NUMBER OF TRANSMISSIONS (MNT)	INPUT RATE [%]	THROUGH-PUT [%]	TOTAL LOSS [%]	ROUND TRIP DELAY AVERAGE [SLOTS]	ROUND TRIP DELAY AVERAGE/HOP [SLOTS]	AVERAGE BUFFER OCCUPANCY [PACKETS]
OFFERED RATE 15%	3	15.83	14.32	0	8.86	2.06	3.20
	6	13.59	13.41	0	8.81	2.17	2.57
	9	18.75	18.04	0	9.50	2.16	3.41
	15	16.83	16.18	10.89	11.13	2.65	3.80
	Variable MNT	15.17	14.75	0	8.18	1.98	2.40
	∞	12.24	6.34	27.87	10.83	2.55	6.59
OFFERED RATE 30%	3	32.83	27.75	6.34	34.12	8.66	7.34
	6	27.34	21.79	12.24	33.38	7.15	9.40
	9	30.37	20.85	16.49	39.00	9.22	11.65
	15	34.03	22.91	14.18	34.12	8.12	11.08
	Variable MNT	30.96	29.12	2.40	17.04	3.93	5.16
	∞	23.00	12.98	6.58	29.75	7.07	15.45

TABLE 1

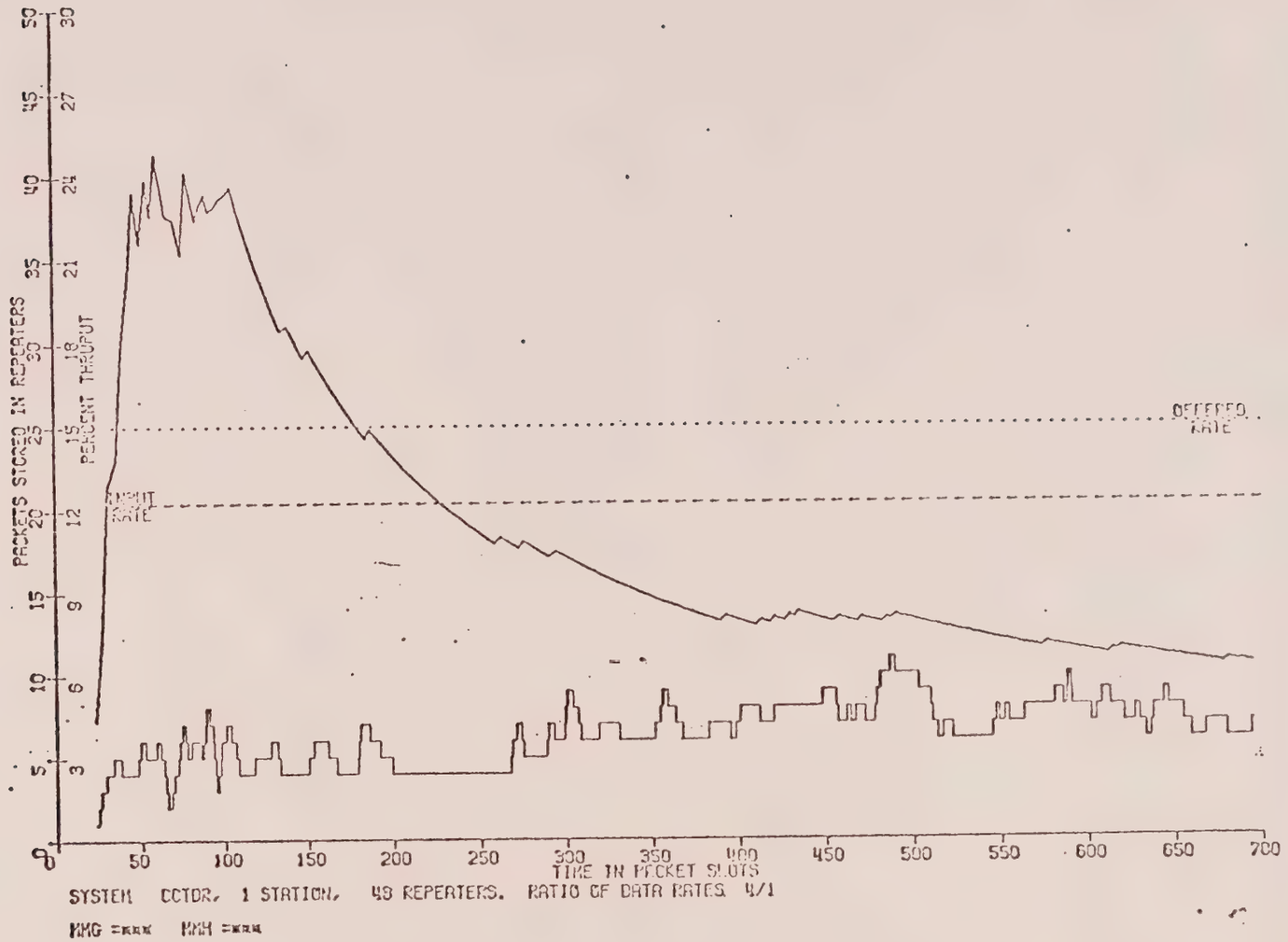

PACKETS STORED IN REPEATERS
PERCENT THROUGHPUT
OFFERED RATE
TIME IN PACKET SLOTS
SYSTEM OCTOR, 1 STATION, 49 REPEATERS. RATIO OF DATA RATES 4/1

FIGURE 3

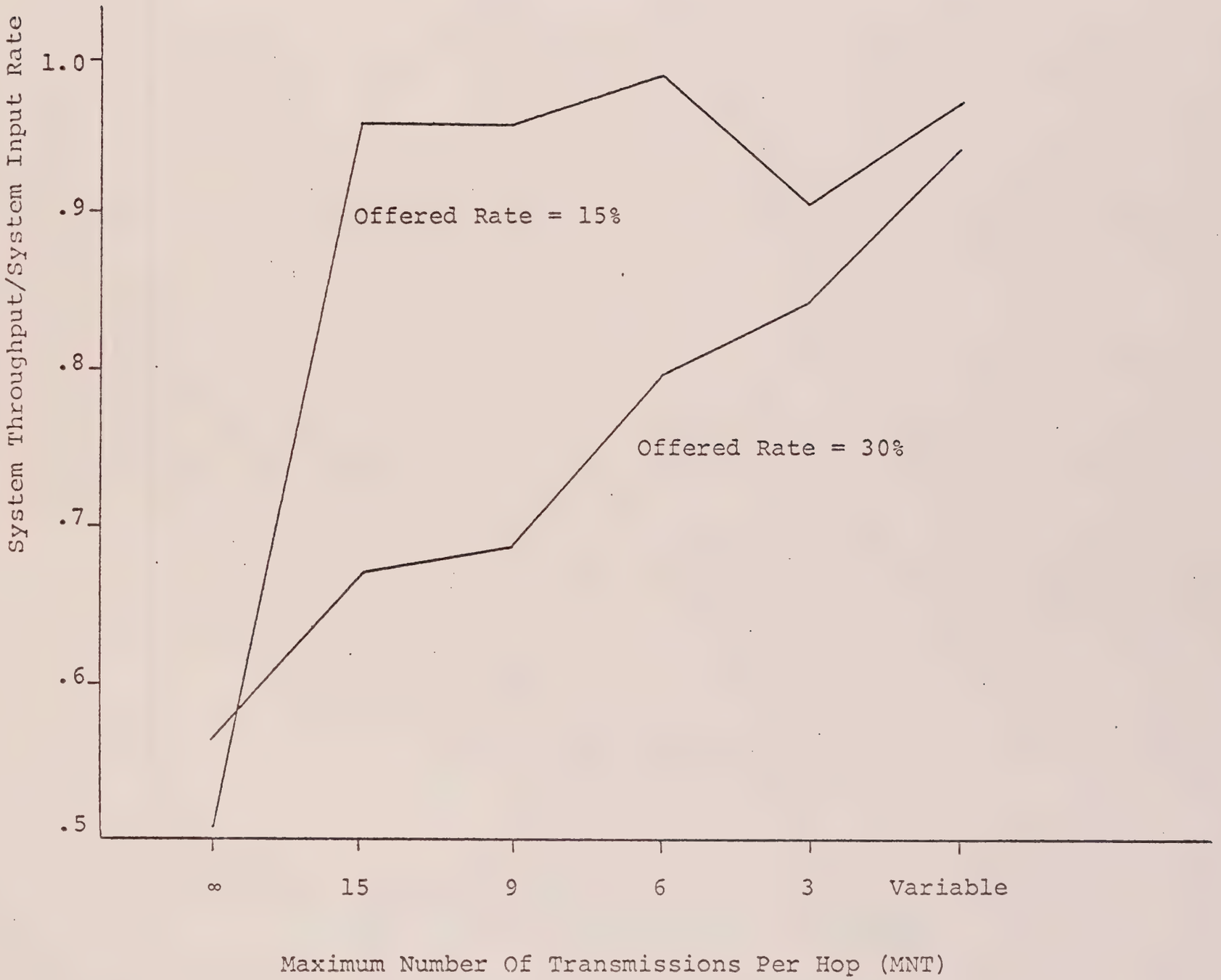

System Throughput/System Input Rate
1.0
.9
.8
.7
.6
.5
Offered Rate = 15%
Offered Rate = 30%
∞
15
9
6
3
Variable
Maximum Number Of Transmissions Per Hop (MNT)

FIGURE 4

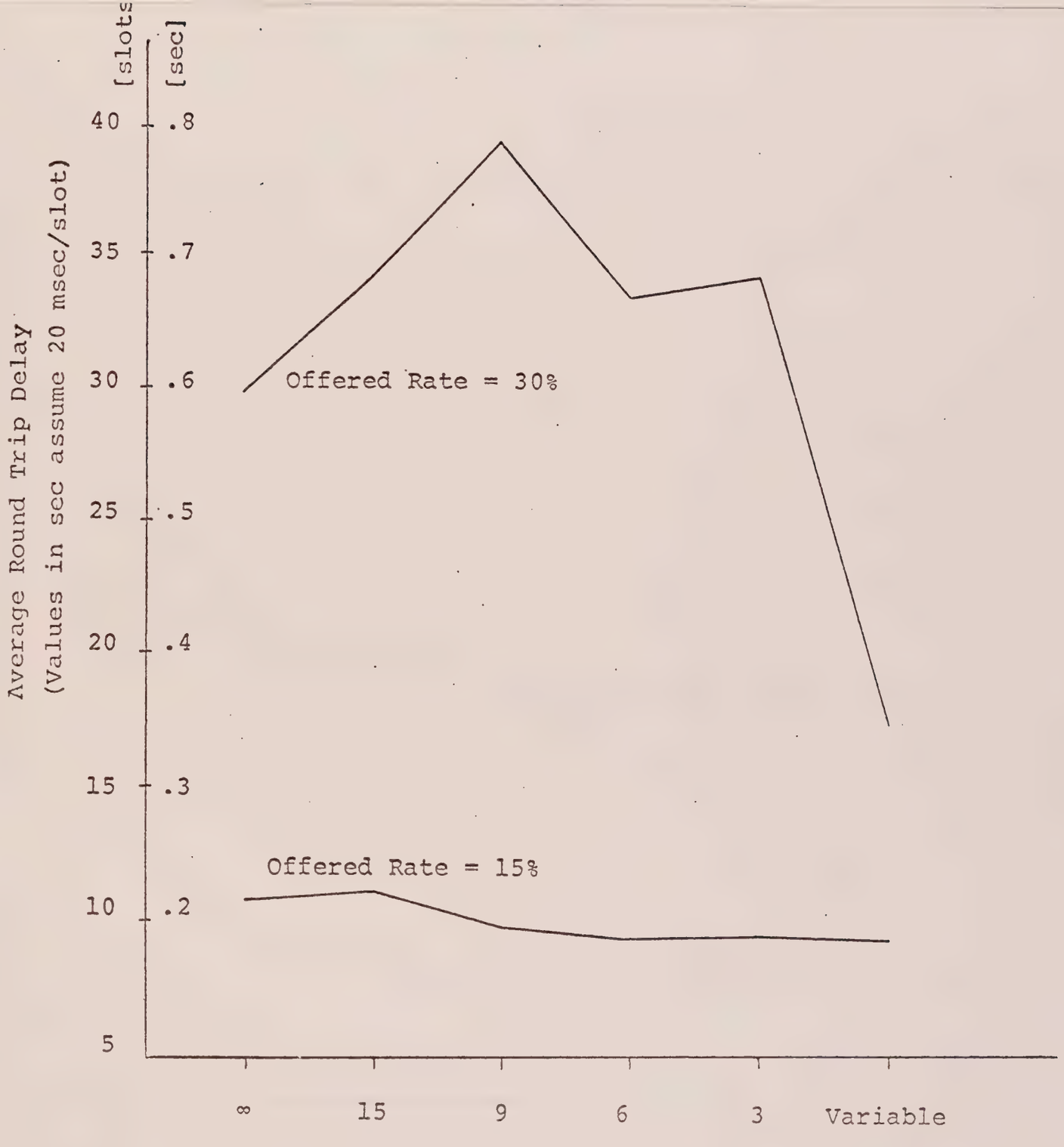

[slots]
[sec]
40
.8
35
.7
30
.6
25
.5
20
.4
15
.3
10
.2
5
Average Round Trip Delay
(Values in sec assume 20 msec/slot)
Offered Rate = 30%
Offered Rate = 15%
∞
15
9
6
3
Variable
Maximum Number Of Transmissions (MNT)

FIGURE 5

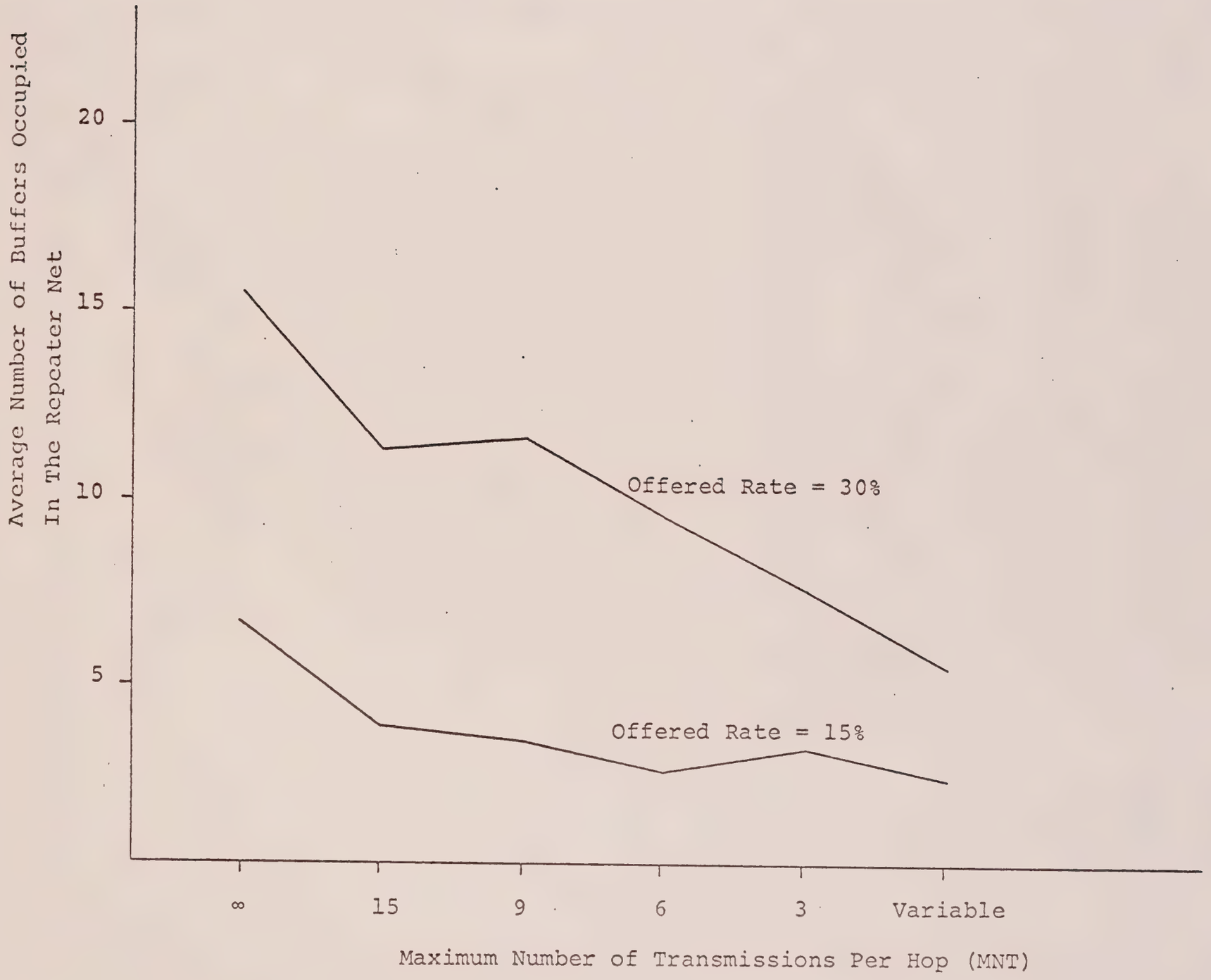
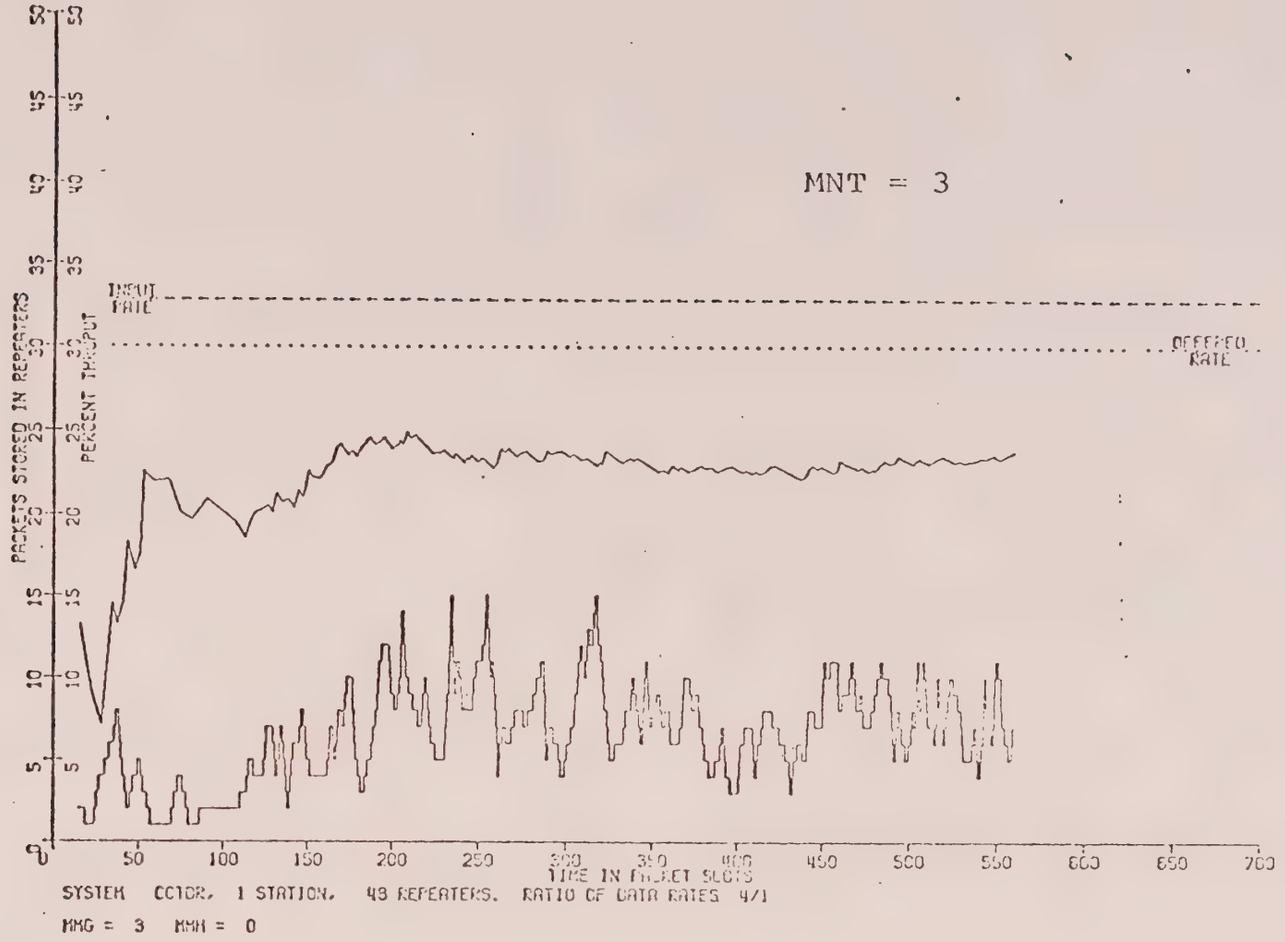

Average Number of Buffers Occupied
In The Repeater Net
20
15
10
5
Offered Rate = 30%
Offered Rate = 15%
∞
15
9
6
3
Variable
Maximum Number of Transmissions Per Hop (MNT)

FIGURE 6


MNT = 3
INPUT RATE
OFFERED RATE
PACKETS STORED IN REPEATERS
PERCENT THRUPUT
TIME IN PACKET SLOTS
SYSTEM CCTOR, 1 STATION, 48 REPEATERS. RATIO OF DATA RATES 4/1
MMG = 3 MMR = 0

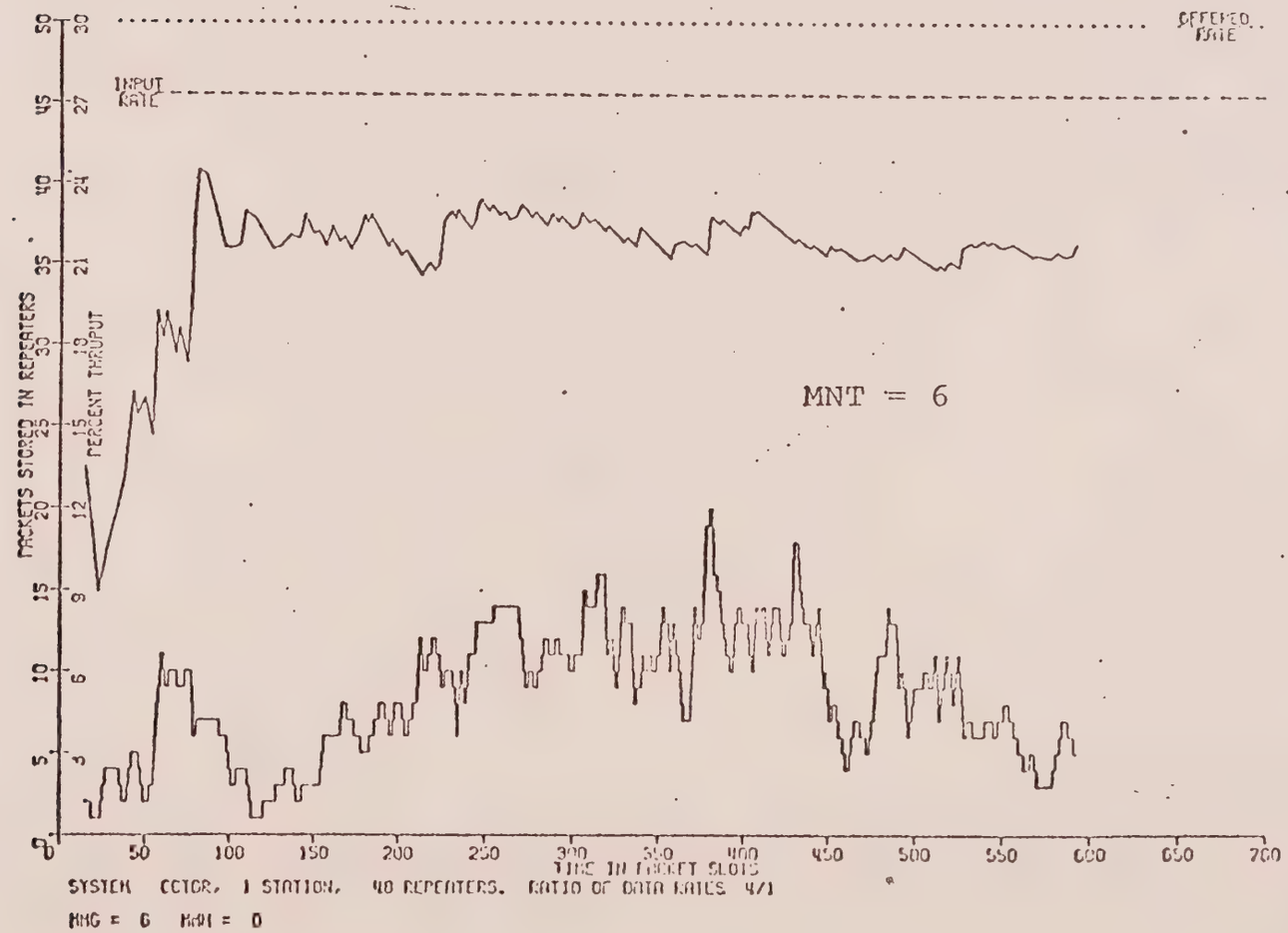
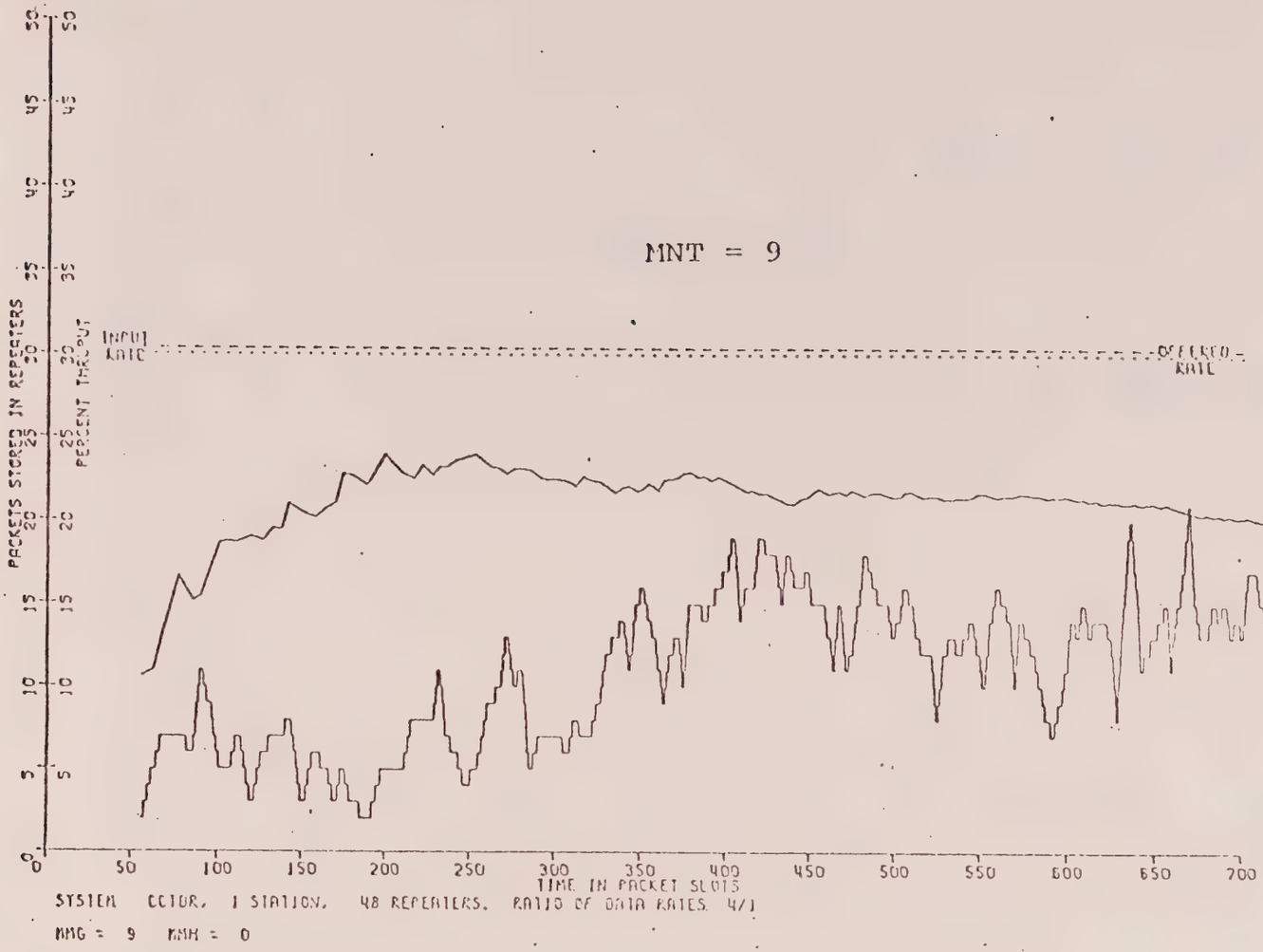

OFFERED RATE
INPUT RATE
MNT = 6
PACKETS STORED IN REPEATERS
PERCENT THRUPUT
TIME IN PACKET SLOTS
SYSTEM CCTOR, 1 STATION, 48 REPEATERS. RATIO OF DATA RATES 4/1
MMG = 6 MMR = 0

FIGURE 7


MNT = 9
PACKETS STORED IN REPEATERS
PERCENT THROUGHPUT
INPUT RATE
DEFERRED RATE
TIME IN PACKET SLOTS
SYSTEM CCTDR, 1 STATION, 48 REPEATERS, RATIO OF DATA RATES 4/1
MNG = 9 MNH = 0

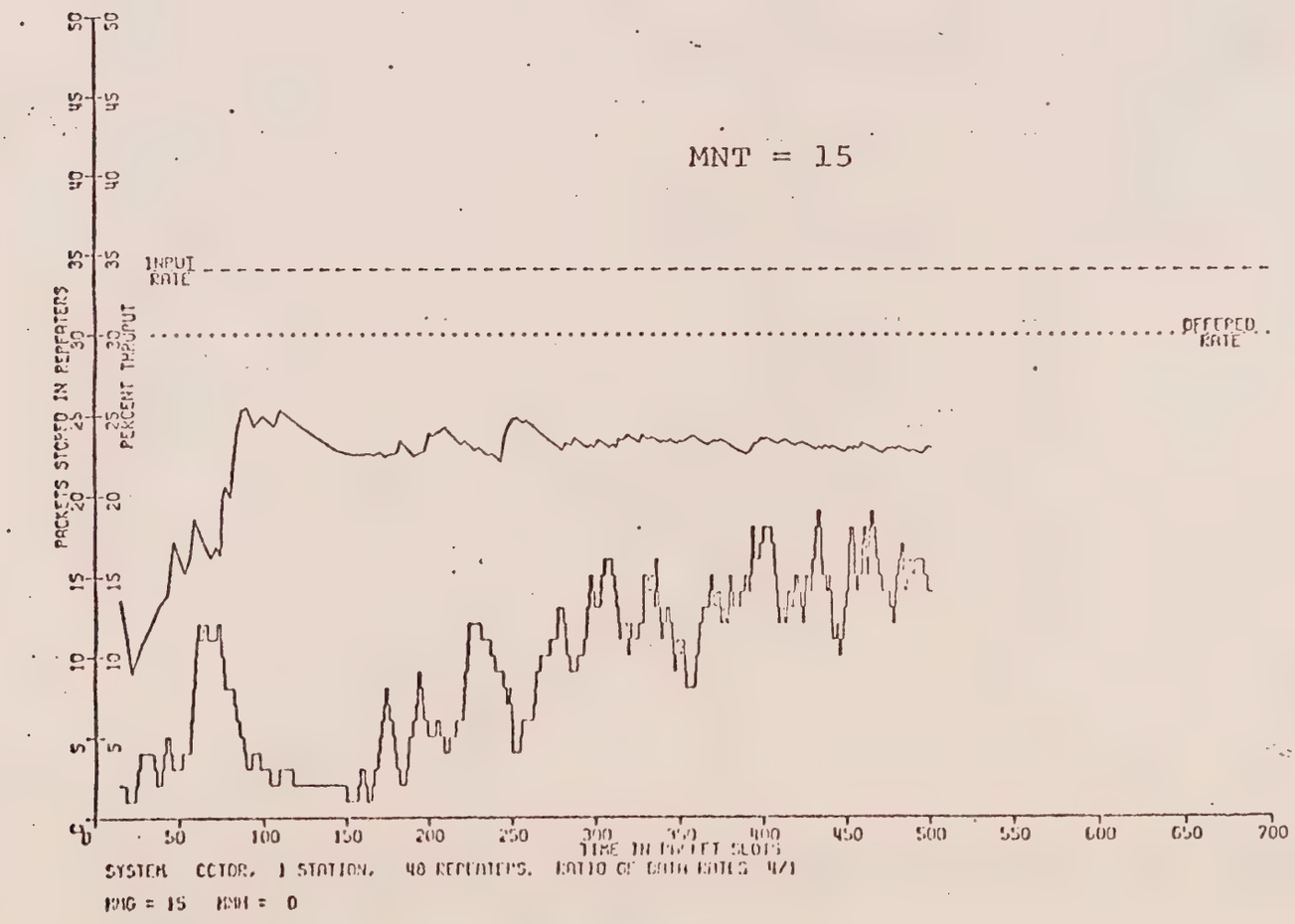
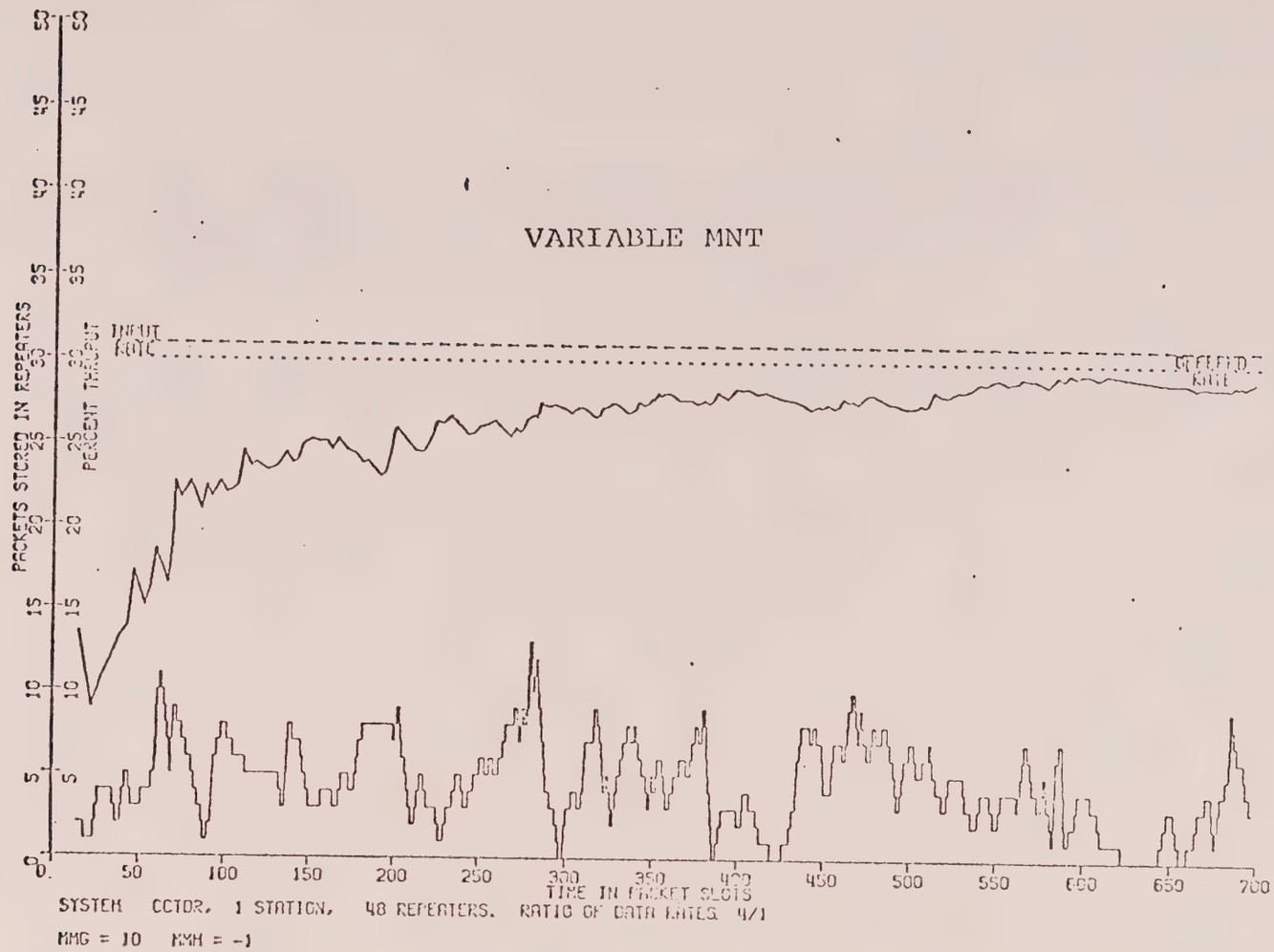

MNT = 15
PACKETS STORED IN REPEATERS
PERCENT THROUGHPUT
INPUT RATE
DEFERRED RATE
TIME IN PACKET SLOTS
SYSTEM CCTDR, 1 STATION, 48 REPEATERS, RATIO OF DATA RATES 4/1
MNG = 15 MNH = 0

FIGURE 8


VARIABLE MNT
PACKETS STORED IN REPEATERS
PERCENT THROUGHPUT
INPUT RATE
DEFERRED RATE
TIME IN PACKET SLOTS
SYSTEM CCTDR, 1 STATION, 48 REPEATERS. RATIO OF DATA RATES 4/1
MMG = 10 MXH = -1

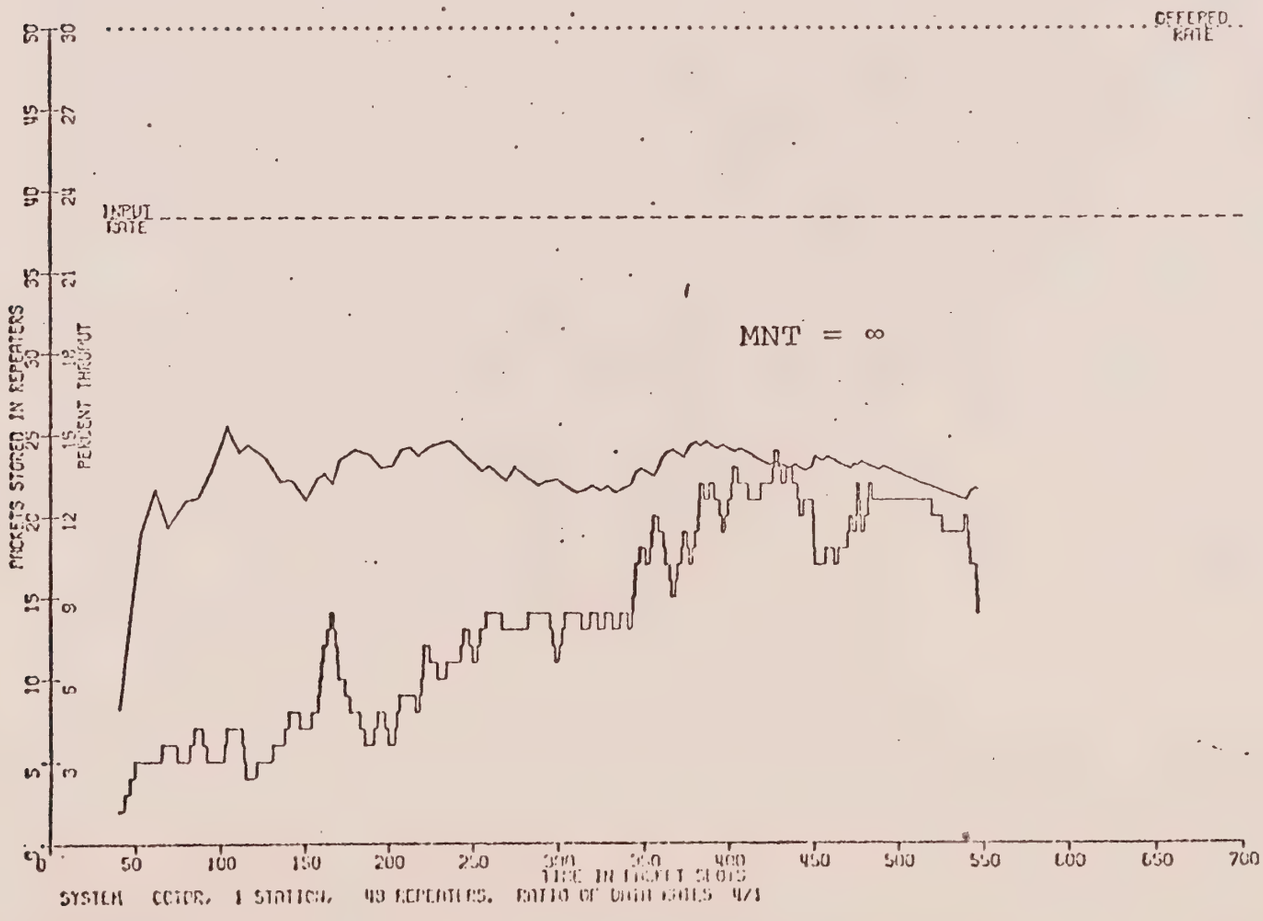

DEFERRED RATE
INPUT RATE
MNT = ∞
PACKETS STORED IN REPEATERS
PERCENT THROUGHPUT
TIME IN PACKET SLOTS
SYSTEM CCTDR, 1 STATION, 48 REPEATERS. RATIO OF DATA RATES 4/1

FIGURE 9

4. PERFORMANCE OF PACKET RADIO SYSTEMS WITH ZERO CAPTURE AND PERFECT CAPTURE RECEIVERS

This section reports on a simulation study for comparing the performance of the packet radio system with zero capture and perfect capture receivers. In the model of the zero capture receiver, it is assumed that if two or more packets overlap in time then all of the packets are received with error. For the perfect capture receiver model, it is assumed that the first packet detected by the device will be received correctly. That is, if several packets overlap in time, it is assumed that all the packets are received with error, apart from the first packet. It is recognized that the perfect capture model is not realistic (e.g., the power of the signals of overlapping packets is not taken into account). However, it is suggested that the qualitative performance of an improved receiver will be similar to what has been observed for the perfect capture model, and the quantitative results may be considered as an upper bound on the improvements in performance that one may expect.

The system parameters, apart for the capture, were kept constant throughout the study. The parameters which define the system are stated in Section 2, a header checksum, the variable MNT of the previous section, and a data rate ratio of 4 to 1.

The receiver of all devices; station, repeater, and terminal was assumed to be the same; namely, either zero or perfect. The zero and perfect capture systems were compared for the following offered rates: 15%, 24%, 30%, 36% and 45%. The number of terminals simulated for the various tests ranged from 40 to 100, and the number of information packets end-to-end acknowledged ranged from 90 to 300. The average number of hops of the terminals from the station (measured) was 3.9 to 4.5.

Table 2 summarizes the performance of the simulation runs used for comparison of the systems. Figure 10 shows the system throughput as a function of the traffic rate offered to the system, for the zero capture and perfect capture receivers. Figure 11 compares the two systems in terms of the average round trip delay, again as a function of the offered rate.

Observing the throughput curves, one can see the following two regions. When the offered rate is less than 30% (approximately) the two systems perform well and each is capable of delivering the offered traffic rate. For example, when the offered rates were 24% and 30%, the zero capture system delivered 22.46% and 29.12%, and the perfect capture system delivered 18.80% (note that the input rate was low, 19.68%) and 28.48%, respectively. Considering the same offered rate interval in the delay curves (Figure 11) shows that the performance of the perfect capture system is significantly better than that of the zero capture system. For the offered rates of 24% and 36%, the average round trip delays were 15.21 and 17.04 for the zero capture system, and 8.13 and 8.02 for the perfect capture system, respectively.

When the offered rate is greater than 30%, one can see from Figure 10 that the throughput of the zero capture system decreases, whereas that of the perfect capture system increases (although at a slower rate). Hence, the performance of the system with perfect capture receivers is superior to that with zero capture receivers both in throughput and delay for "high" offered rates. In Figure 11, one can see that the difference in delays between the two systems increases as a function of the offered rate.

Figure 12 shows the ratio of throughput to input rate as a function of the offered rate. This measure can be used to demonstrate the rate of performance degradation. It can be seen that

the perfect capture system degrades "gracefully" whereas in the zero capture system there is a relatively fast degradation above the offered rate at which its maximum throughput is obtained. This essentially implies that a system with zero capture receivers must have more sophisticated stability control procedures and that it should be designed to operate below its maximum throughput.

As a final comparison note, the self regulation of the input rate is considered. From Table 2, one can see that when the offered rate is above 30%, the difference between the offered rate and the input rate for the zero capture system increases, whereas for the perfect capture system there is no significant trend. This seems to indicate that the zero capture system has an inherent control over the input rate and would tend to block terminals when the system is locally overloaded.

Figure 13 shows the average buffer occupancy in the entire repeater network. There are no significant differances and no conclusions are made. Figures 14 through 18 show the throughput and total number of packets stored in repeaters as a function of time, for the various offered rates.

	OFFERED RATE [%]	INPUT RATE [%]	THROUGH-PUT [%]	TOTAL LOSS [%]	ROUND TRIP DELAY AVERAGE [SLOTS]	ROUND TRIP DELAY AVERAGE/HOP [SLOTS]	AVERAGE BUFFER OCCUPANCY [PACKETS]
ZERO CAPTURE	15	15.17	14.75	0	8.18	1.98	2.40
	24	22.97	22.46	.33	15.21	3.47	4.63
	30	30.96	29.12	2.40	17.04	3.93	5.16
	36	32.31	22.37	18.81	26.80	6.52	8.75
	45	38.92	21.05	16.98	33.96	7.63	11.50
PERFECT CAPTURE	15	15.70	15.44	0	6.15	1.50	2.95
	24	19.68	18.80	0	8.13	2.07	3.42
	30	30.07	28.48	2.22	8.02	1.88	4.82
	36	35.26	31.66	7.87	10.52	2.59	6.72
	45	45.18	32.66	1.65	17.84	4.15	10.56

TABLE 2

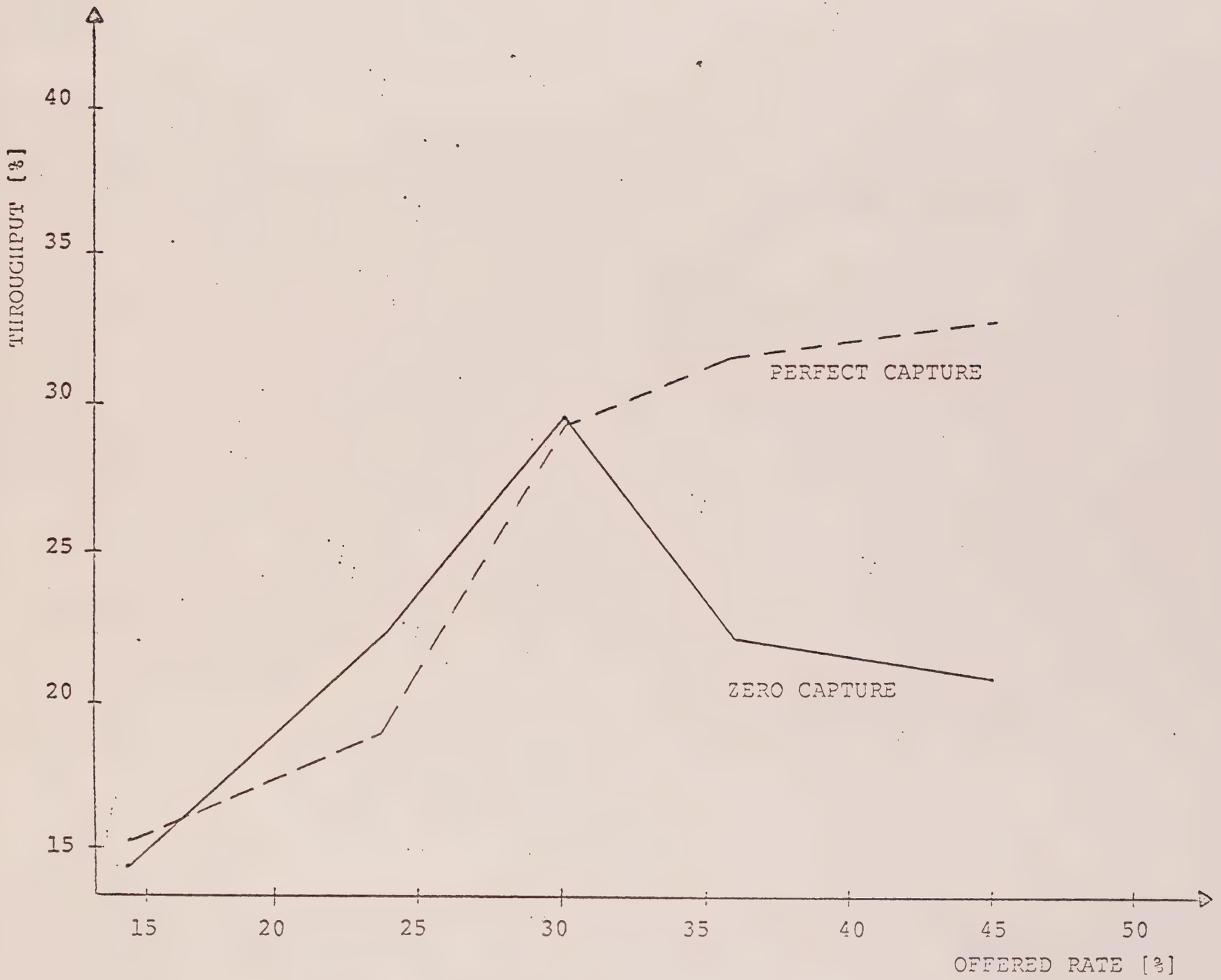

THROUGHPUT [%]
40
35
30
25
20
15
PERFECT CAPTURE
ZERO CAPTURE
15
20
25
30
35
40
45
50
OFFERED RATE [%]

FIGURE 10

AVERAGE ROUND TRIP DELAY
(VALUES IN SEC ASSUME 20 MSEC/SLOT)
[SLOTS]
[SEC]
35
30
25
20
15
10
5
.7
.6
.5
.4
.3
.2
.1
ZERO CAPTURE
PERFECT CAPTURE
15
20
25
30
35
40
45
50
OFFERED RATE [%]

FIGURE 11

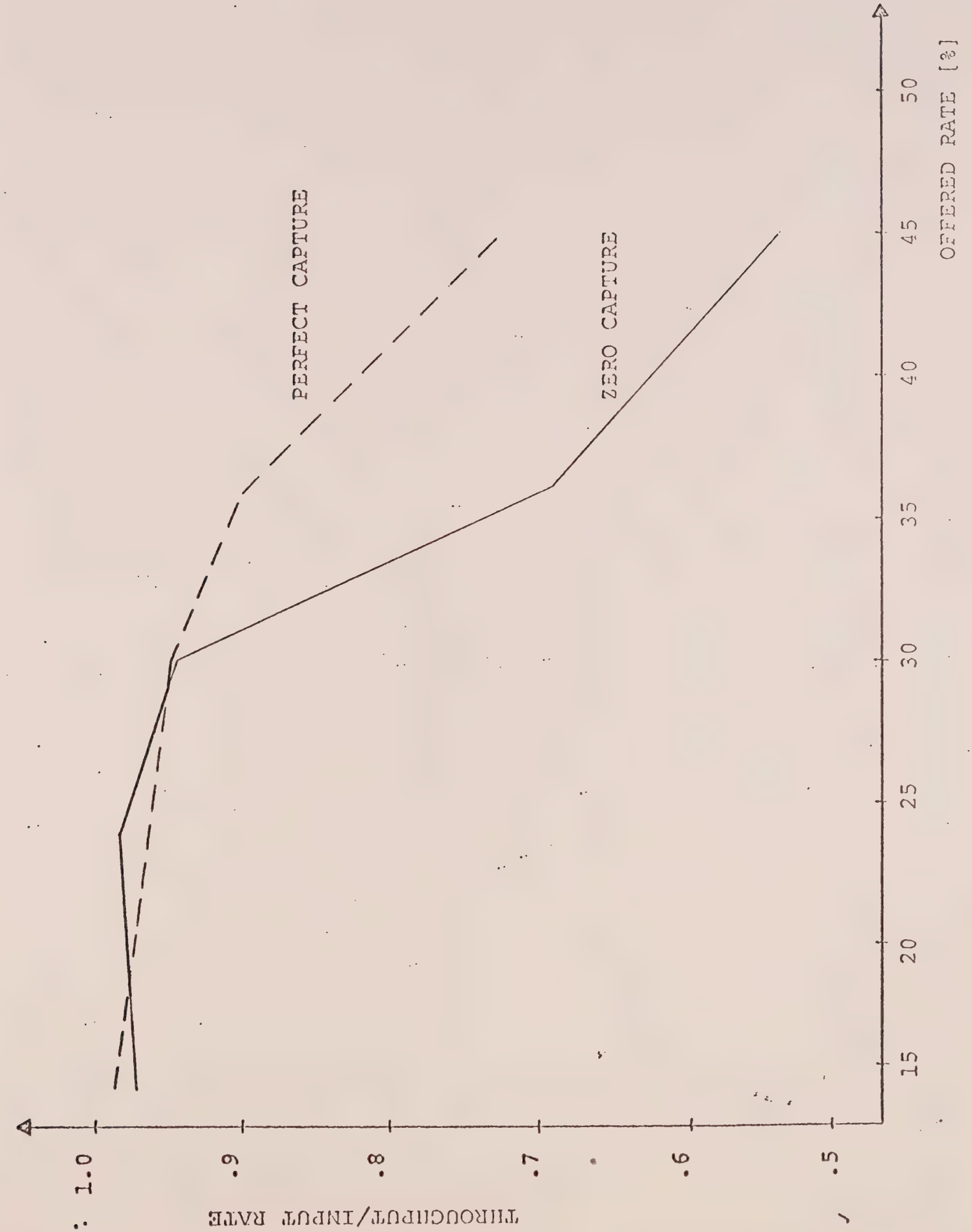

THROUGHPUT/INPUT RATE
1.0
.9
.8
.7
.6
.5
15
20
25
30
35
40
45
50
OFFERED RATE [%]
PERFECT CAPTURE
ZERO CAPTURE

FIGURE 12

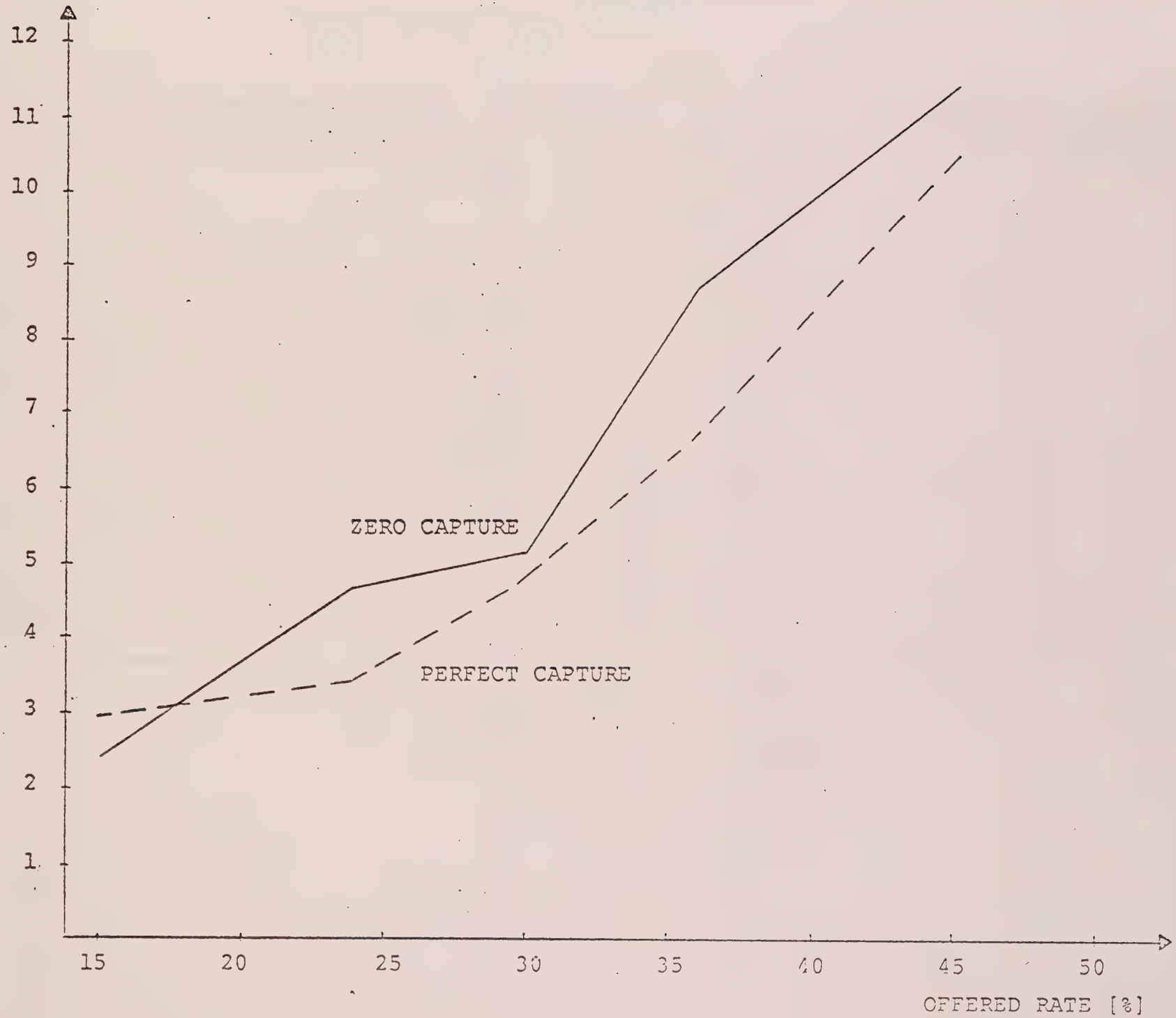
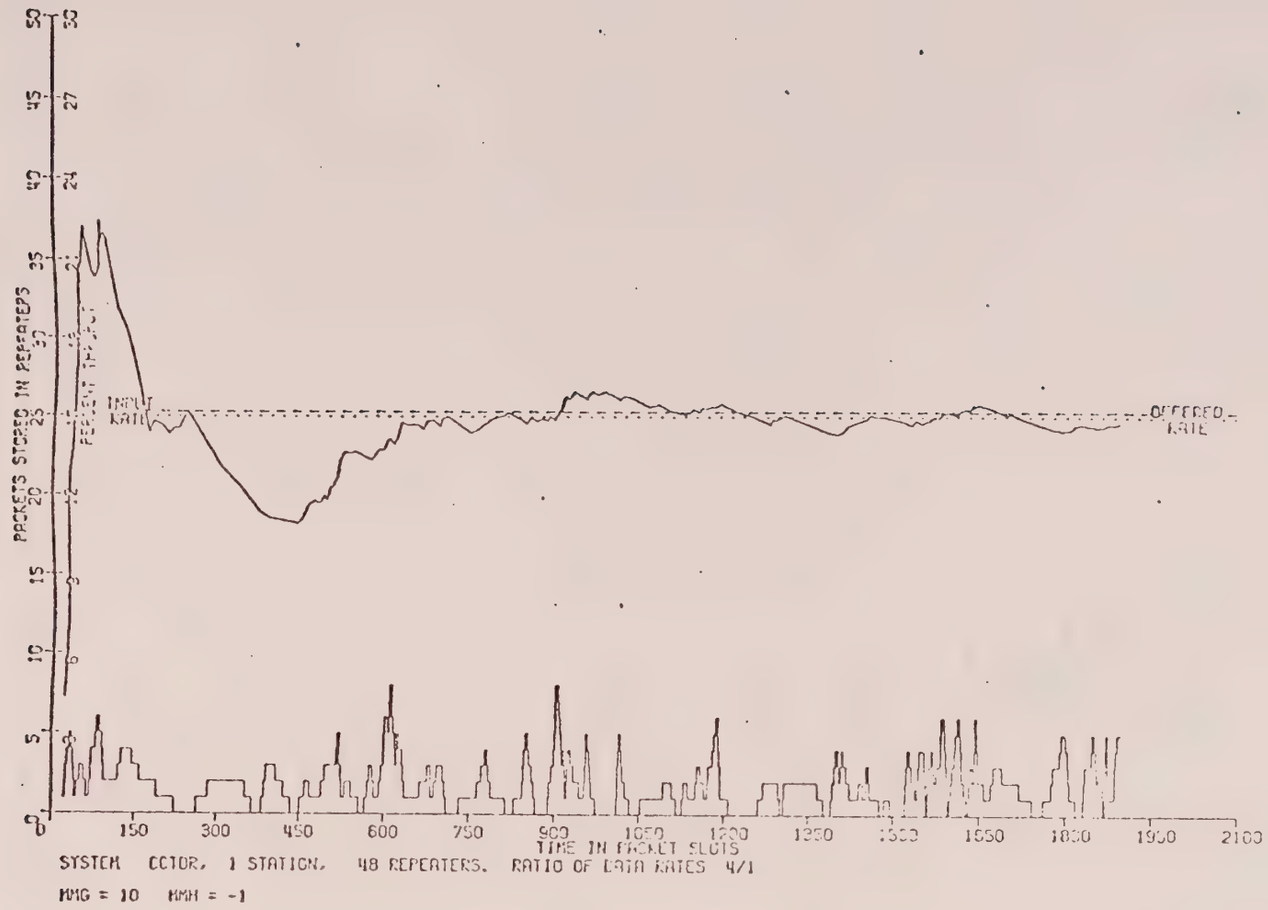
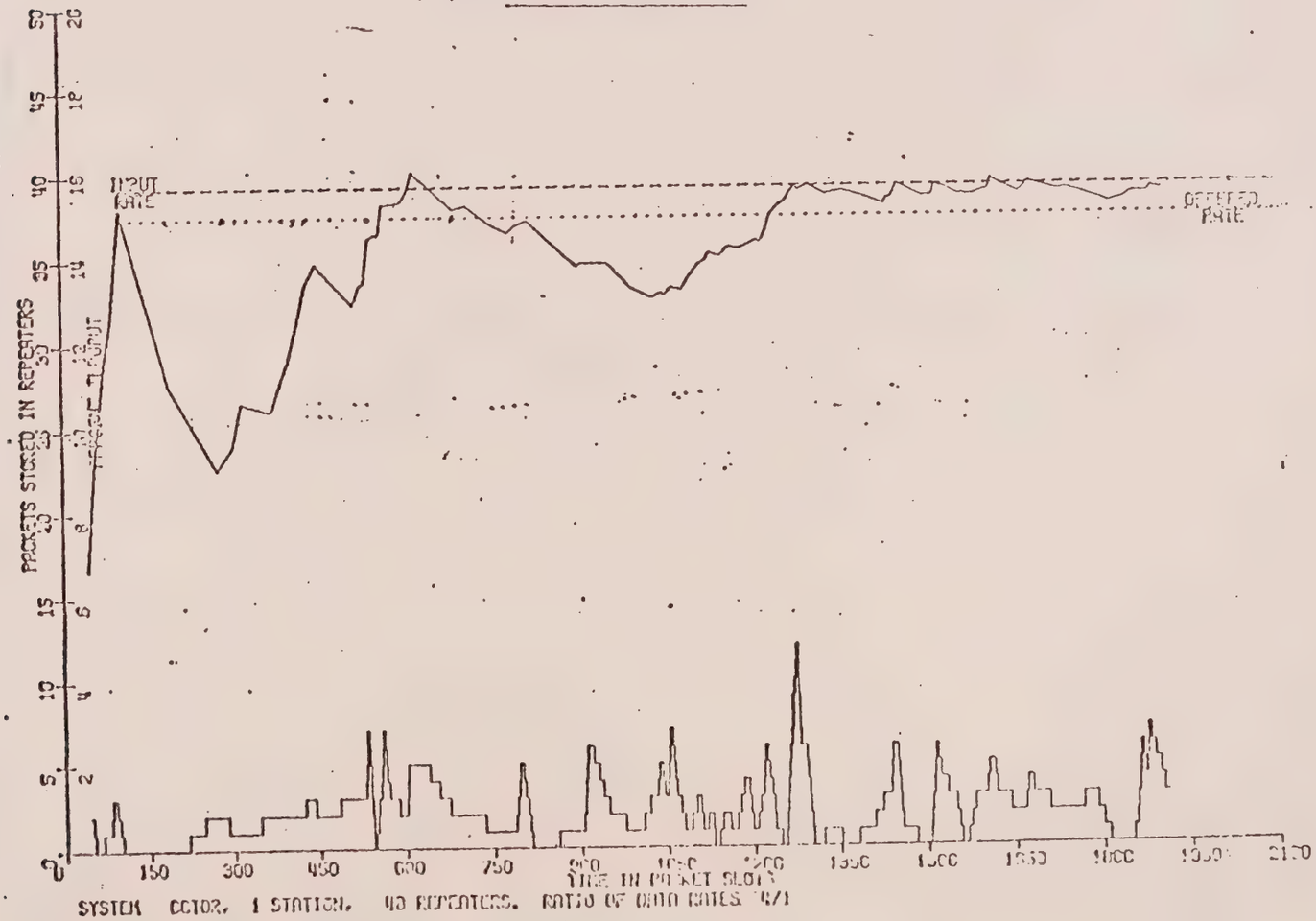

AVERAGE NUMBER OF BUFFERS
OCCUPIED IN THE REPEATER NET
12
11
10
9
8
7
6
5
4
3
2
1
ZERO CAPTURE
PERFECT CAPTURE
15
20
25
30
35
40
45
50
OFFERED RATE [%]

FIGURE 13

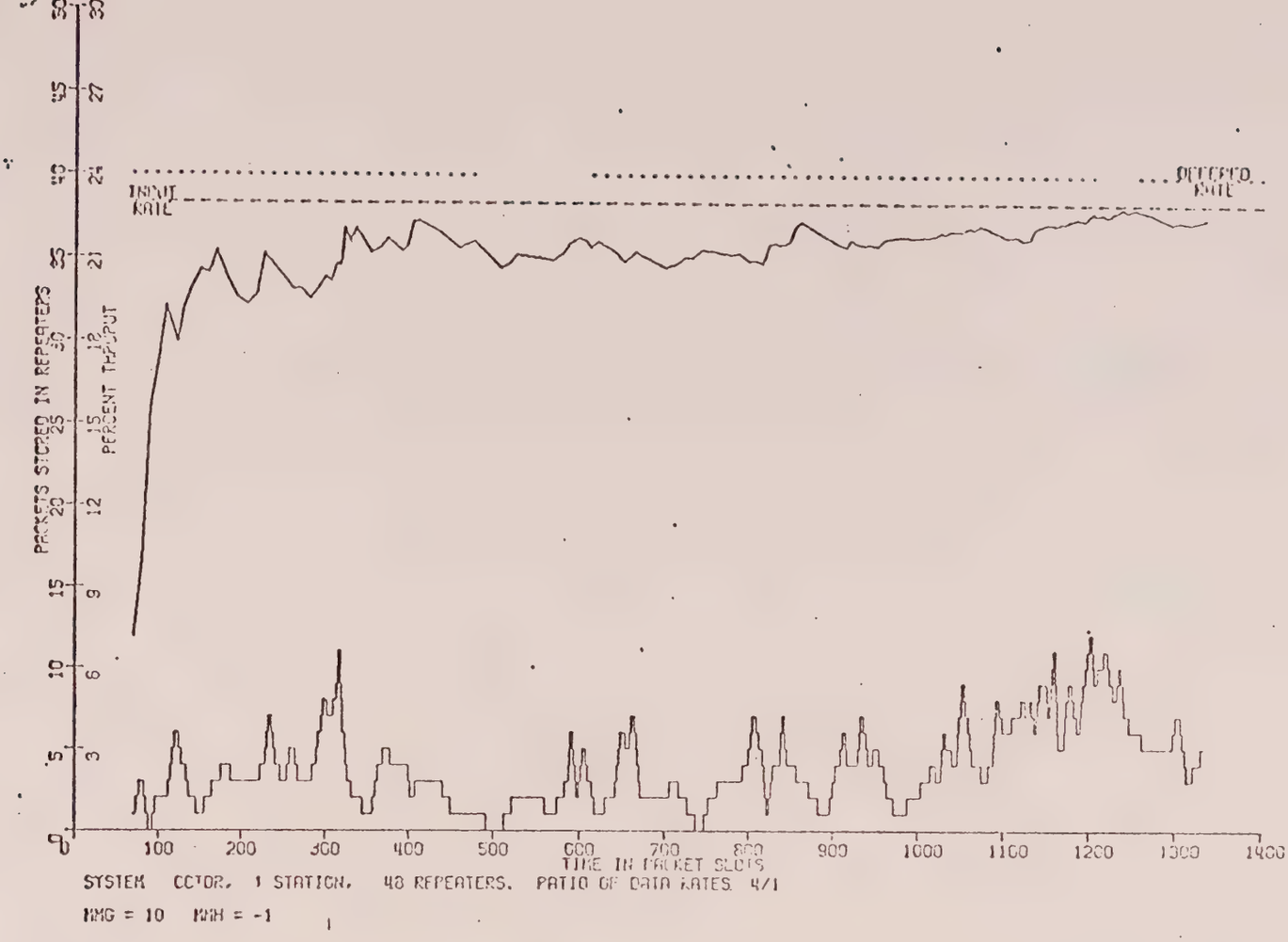


(a) ZERO CAPTURE

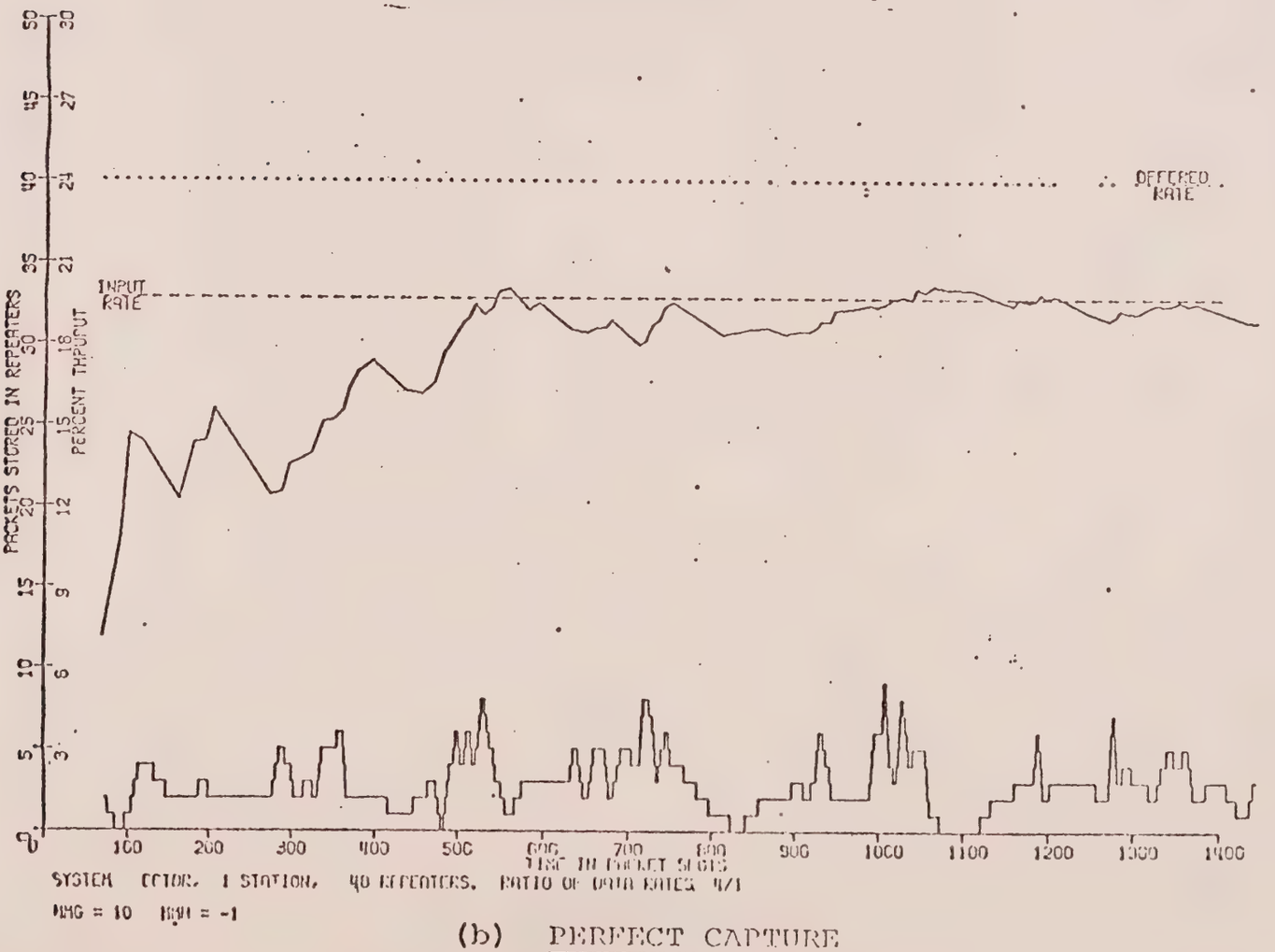


(b) PERFECT CAPTURE

FIGURE 14

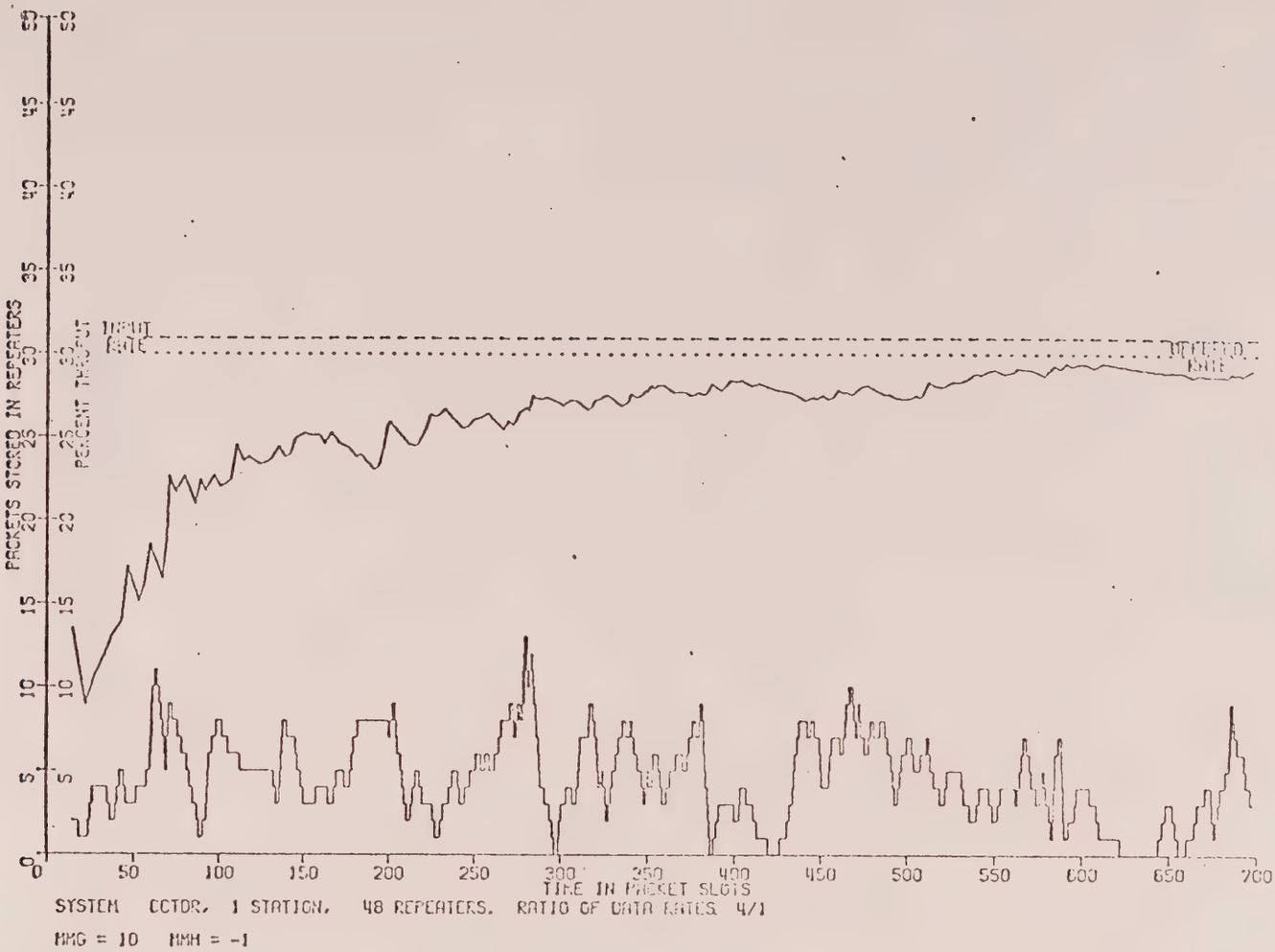


(a) ZERO CAPTURE

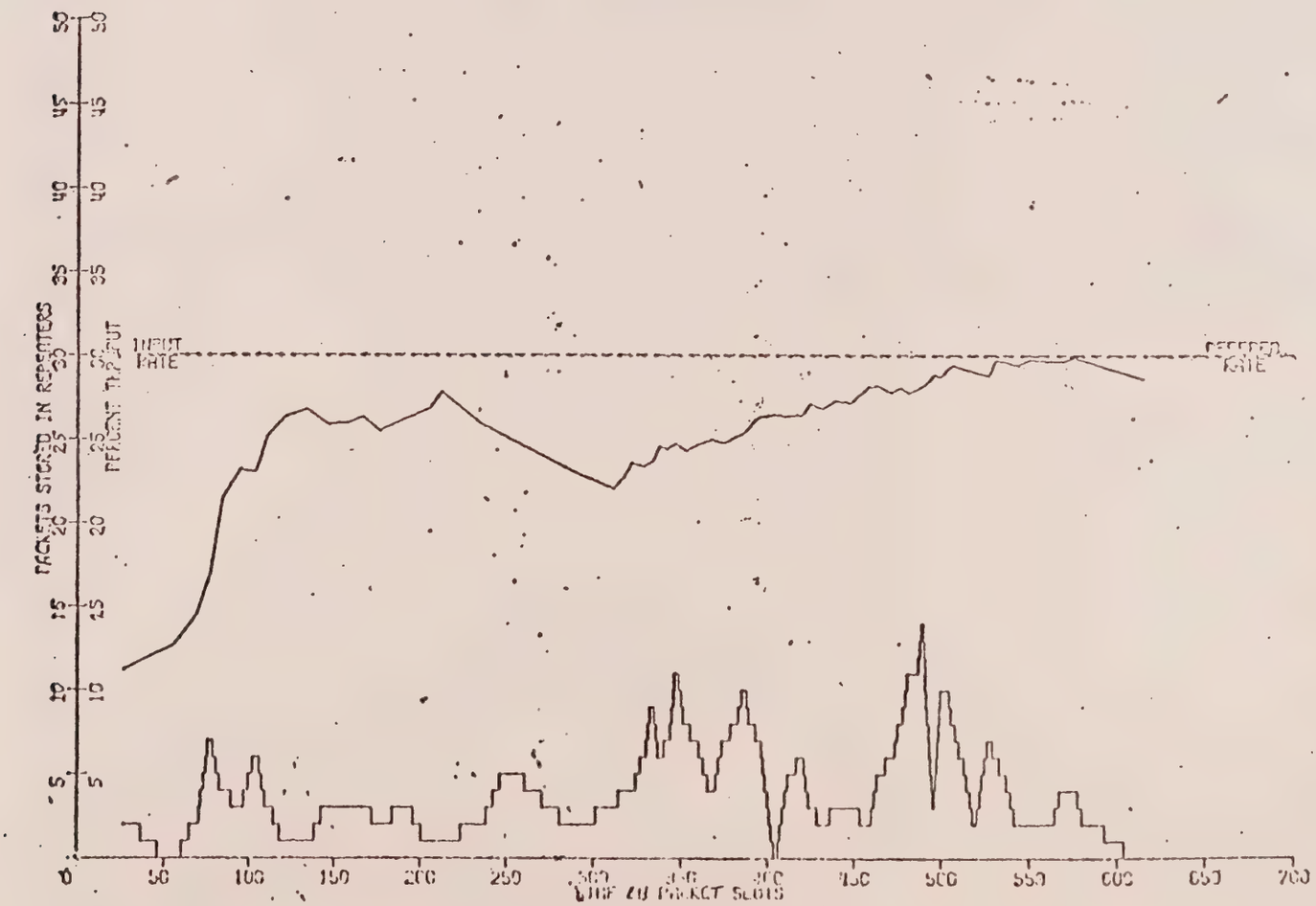


(b) PERFECT CAPTURE

FIGURE 15

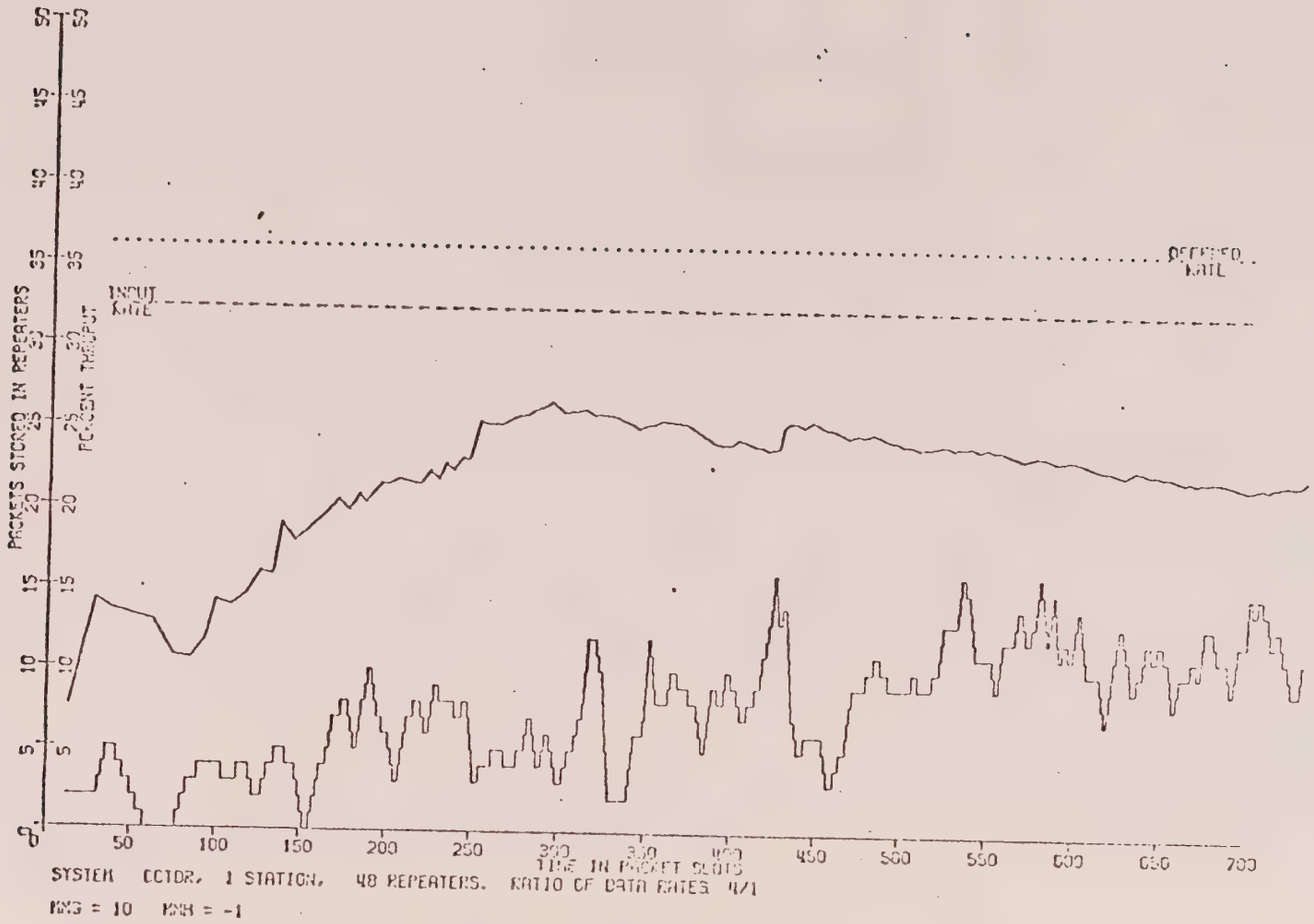


(a) ZERO CAPTURE

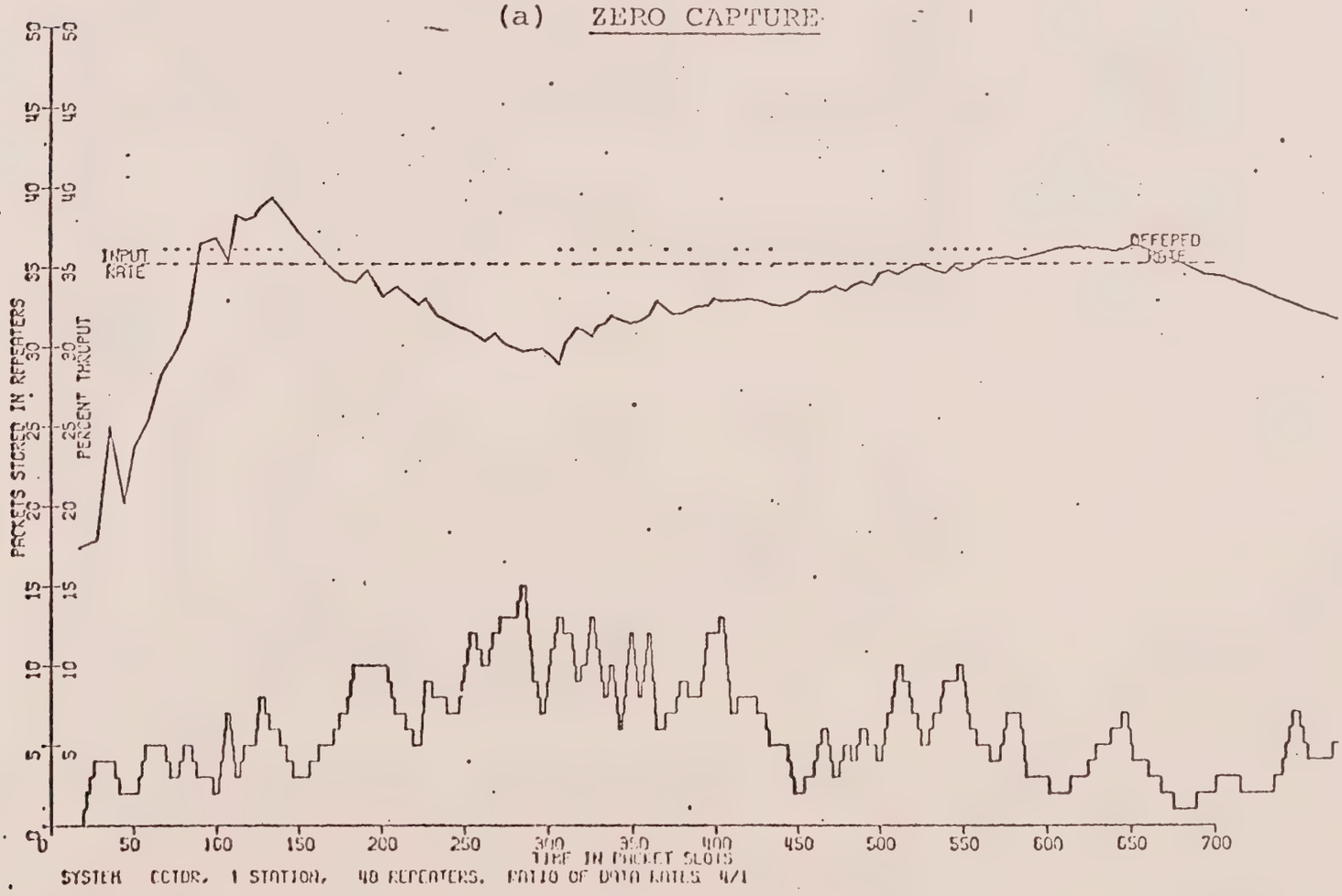


(b) PERFECT CAPTURE

FIGURE 16

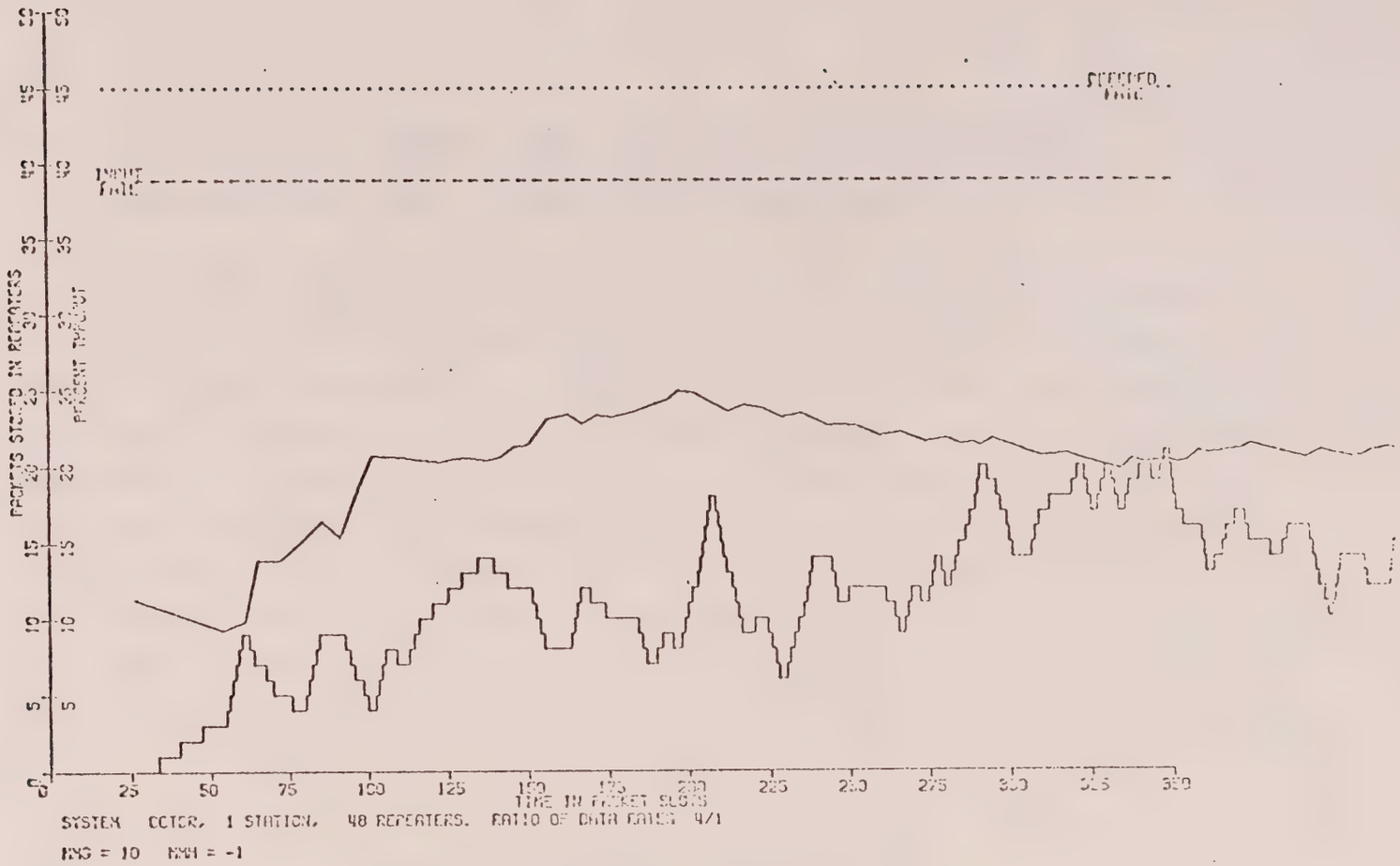


(a) ZERO CAPTURE

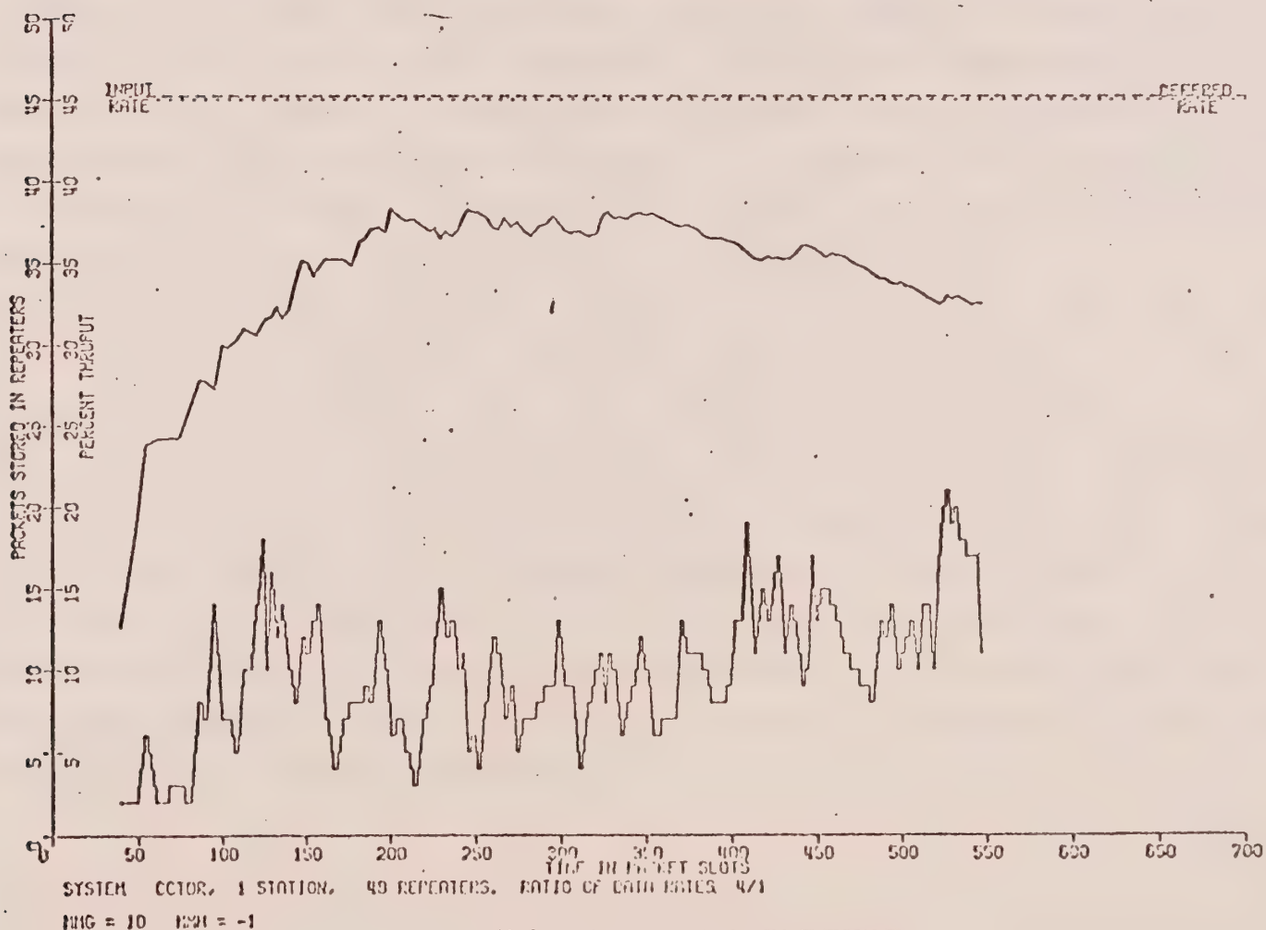


(b) PERFECT CAPTURE

FIGURE 17



(a) ZERO CAPTURE



(b) PERFECT CAPTURE

FIGURE 18

5. COMPARISON OF PACKET RADIO SYSTEMS WITH HOP-BY-HOP ACKS BASED ON HEADER AND PACKET CHECKSUMS

The modelling by simulation of the two alternative schemes for Hop-by-Hop Acknowledgments (HBH Acks) concerns the time at which the receiving device (station, repeater, terminal) examines the Header content, and hence decides whether a HBH Ack has been received. A packet format with two separate checksums, one for the header and one for the entire packet, was stipulated in the early stages of the packet radio project. This was in part to conform with a similar implementation done in the ALOHA System [Abramson, 70]. The ALOHA System is a single hop system and the objective of the header checksum was to enable the identification of the terminal which sent a packet in case the complete packet was received in error. In the packet radio system, the header checksum is utilized for a different purpose, namely to determine the HBH Ack.

Apart from the checksum the systems were identical as defined in Section 2, with zero capture receivers and the variable MNT scheme. The systems were compared for offered rates of 15%, 24%, 30%, and 36%. Table 3 summarizes the performance measures for the two systems, and Figures 19 through 22 compare the systems in terms of throughput, delay, throughput to input rate ratio, and buffer occupancy; all as a function of the offered rate.

It is evident from the figures as anticipated, that the system with the header checksum performs better than without it. The difference in performance, however, is larger than we have anticipated. From Figure 19 one can see that the capacity (maximum throughput) of the system without a header checksum is approximately 22% whereas that of the system with a header checksum is approximately 30%. The difference in the average round-trip delay as a function of the offered rate (Figure 20) is less significant. However, one should note that the delays are for different values of throughput which correspond to those shown in Figure 19.

It is important to note that the improvement is gained only for packets which include text. Hence the difference in performance depends on two parameters: the relative header size in an average packet and the fraction of packets which contain text. In the simulation program there are two packet sizes; a short packet which includes a header only, and a long packet of which the header is 10% of the packet size. The fraction of header size packets in the packet radio system is not yet known. It would depend on the end-to-end protocol and upon the initialization and control schemes which will be implemented.

	OFFERED RATE [%]	INPUT RATE [%]	THROUGH-PUT [%]	TOTAL LOSS [%]	ROUND TRIP DELAY AVERAGE [SLOTS]	ROUND TRIP DELAY AVERAGE/HOP [SLOTS]	AVERAGE BUFFER OCCUPANCY [PACKETS]
HBH ACK BASED ON HEADER CHECKSUM	15	15.17	14.75	0	8.18	1.98	2.40
	24	22.97	22.46	.33	15.21	3.47	4.63
	30	30.96	29.12	2.40	17.04	3.93	5.16
	36	32.31	22.37	18.81	26.80	6.52	8.75
	45	38.92	21.05	16.98	33.96	7.63	11.50
HBH ACK BASED ON PACKET CHECKSUM	15	13.32	13.09	0	7.91	1.92	2.75
	24	21.06	19.97	0	12.49	2.96	6.89
	30	24.99	18.86	0	21.37	5.51	7.77
	36	28.23	17.91	4.00	29.76	7.10	10.02

TABLE 3

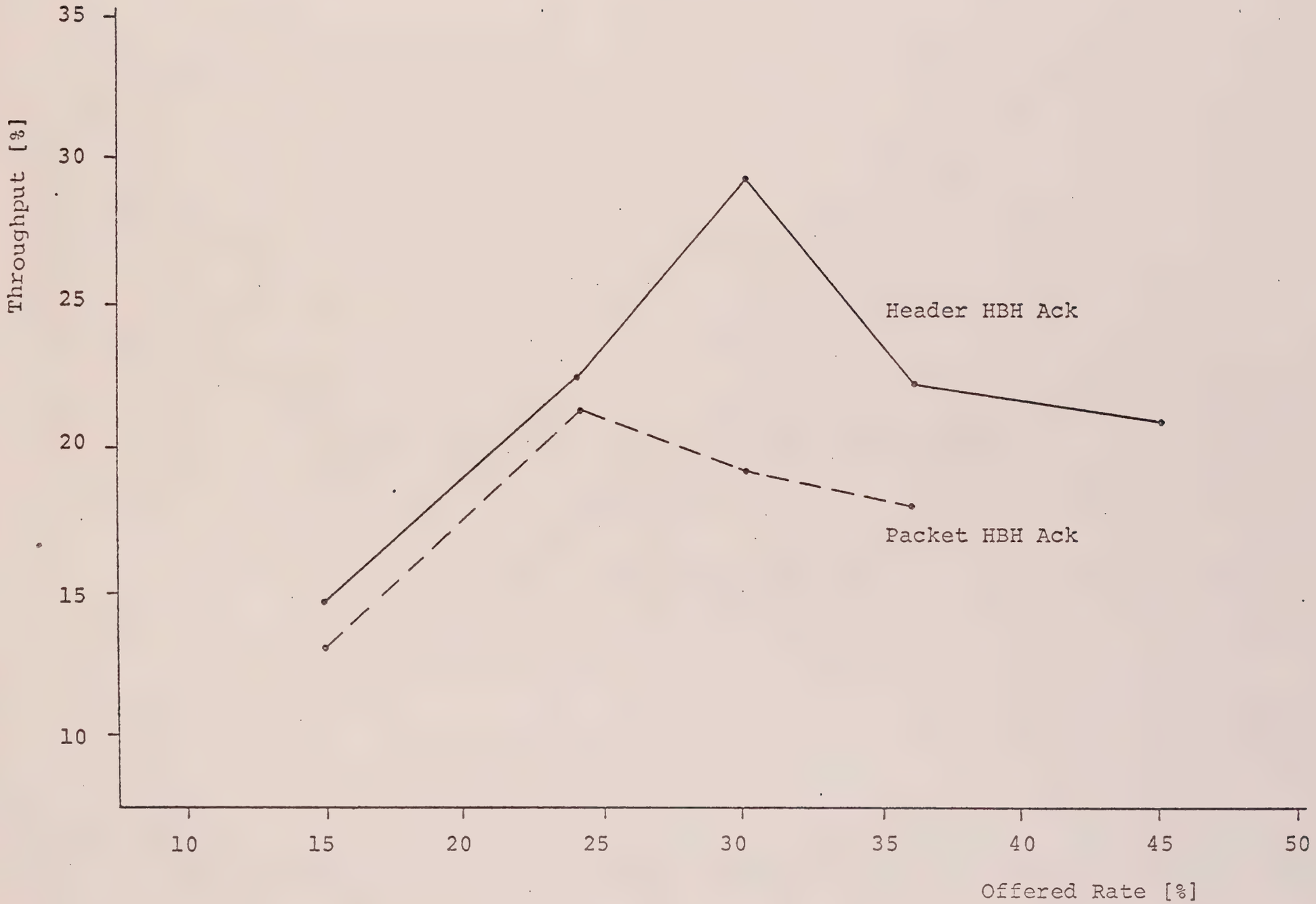

35
30
25
20
15
10
Throughput [%]
Header HBH Ack
Packet HBH Ack
10
15
20
25
30
35
40
45
50
Offered Rate [%]

FIGURE 19

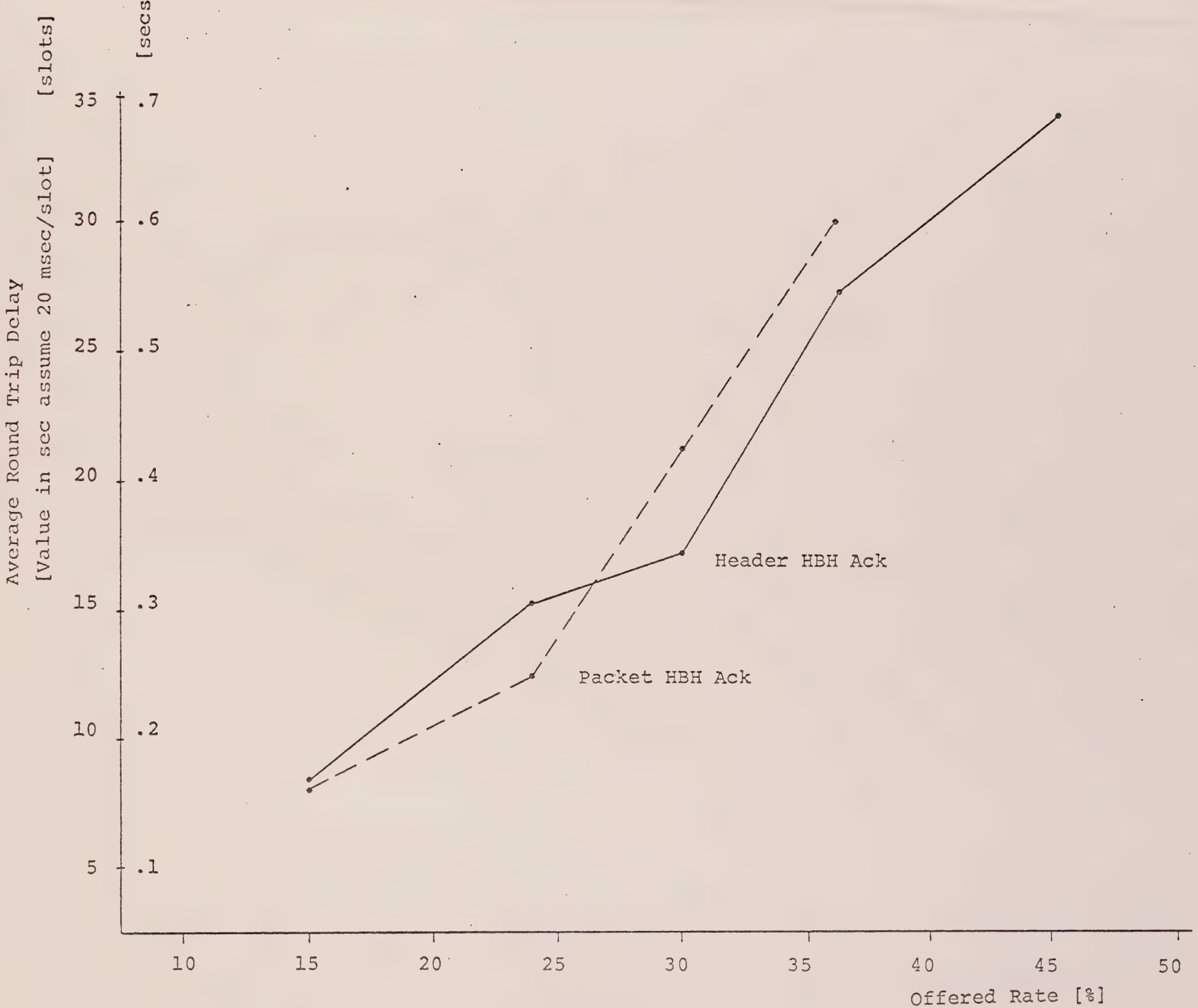

Average Round Trip Delay
[Value in sec assume 20 msec/slot]
[slots]
[secs]
35
30
25
20
15
10
5
.7
.6
.5
.4
.3
.2
.1
Header HBH Ack
Packet HBH Ack
10
15
20
25
30
35
40
45
50
Offered Rate [%]

FIGURE 20

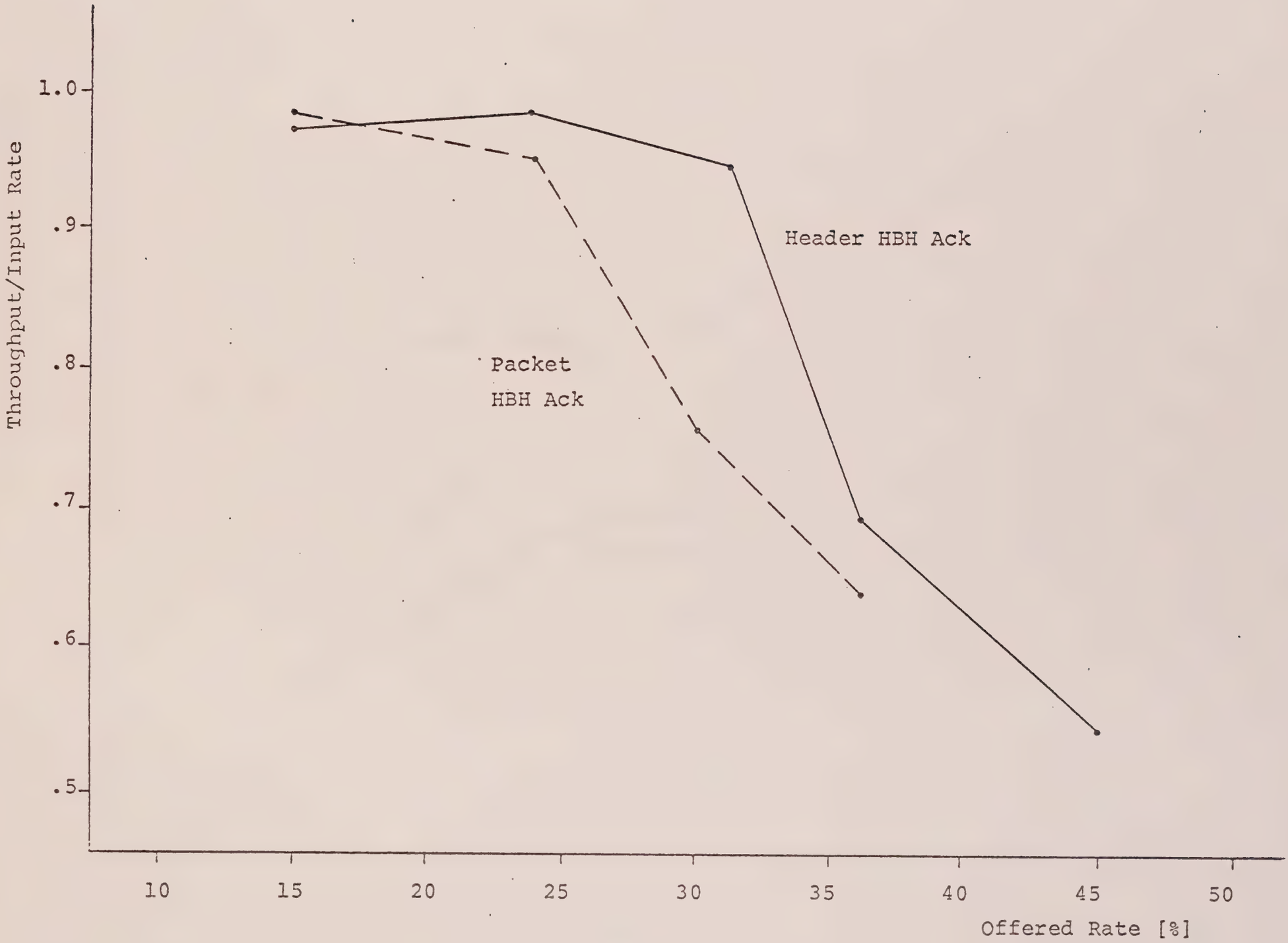

Throughput/Input Rate
1.0
.9
.8
.7
.6
.5
Header HBH Ack
Packet
HBH Ack
10
15
20
25
30
35
40
45
50
Offered Rate [%]

FIGURE 21

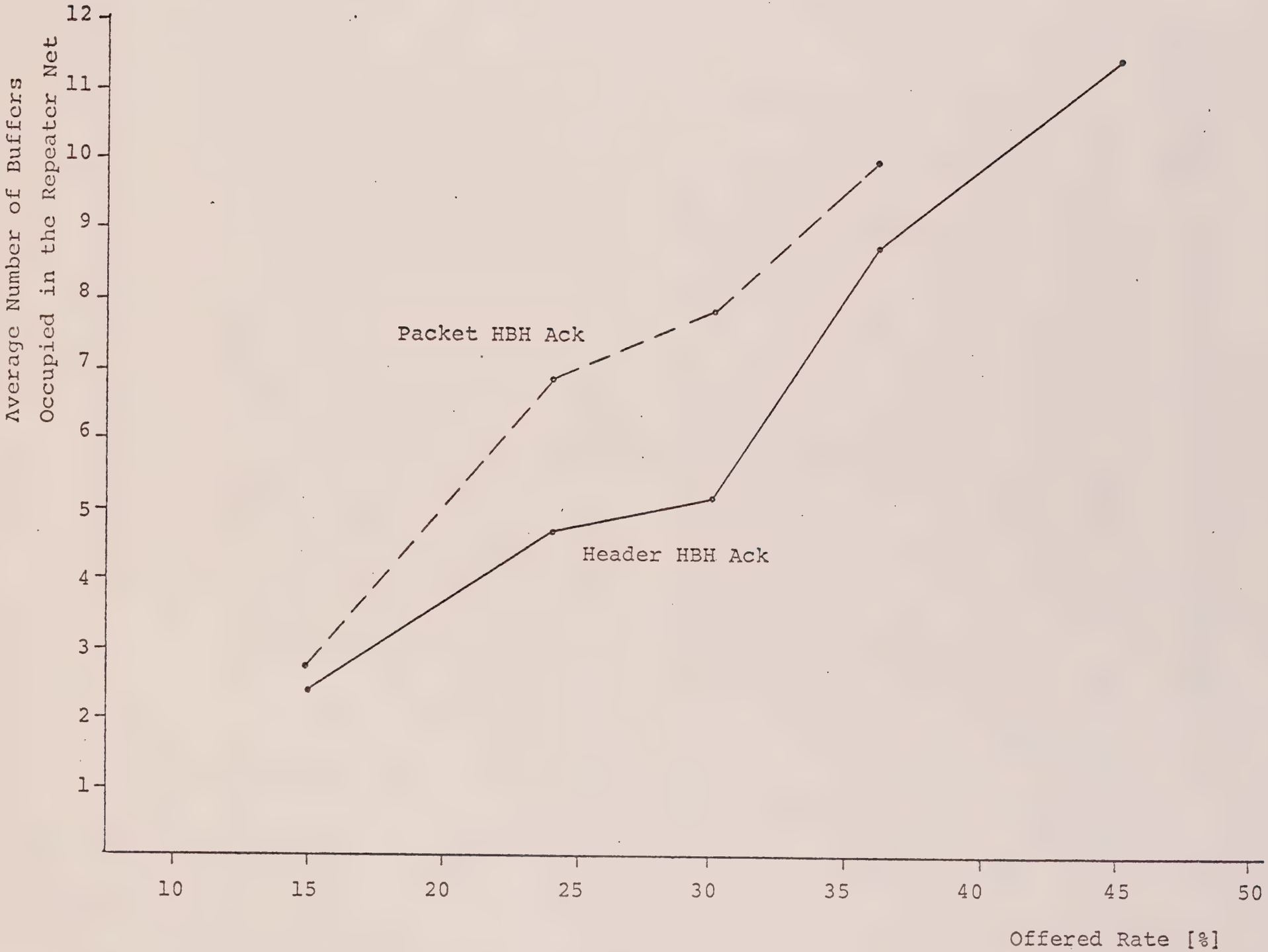

Average Number of Buffers
Occupied in the Repeater Net
12
11
10
9
8
7
6
5
4
3
2
1
Packet HBH Ack
Header HBH Ack
10
15
20
25
30
35
40
45
50
Offered Rate [%]

FIGURE 22

6. PERFORMANCE OF PACKET RADIO SYSTEMS AS A FUNCTION OF DATA RATES

One of the major issues in the development of the packet radio system involves the determination of the data rates for the low and high data rate channels.* Theoretical considerations suggest that the rate of improvement in system performance (e.g., maximum throughput) should decrease as a function of the high data rate, given that the low data rate is kept constant. For example, when the high data rate is increased beyond a certain value, it is anticipated that the system bottleneck will become the low data rate channel. Hence, additional increase in the high data rate may not be economically justifiable. Furthermore, the performance of the carrier-sense multiple access schemes [Kleinrock, 75] are sensitive to the ratio of the propagation time between devices to the packet transmission time. Thus, assuming a fixed topology, an increase in the data rate results in an increase in the above ratio which tends to reduce the efficiency of the channel.

In this section we study experimentally (by simulation) the performance of the packet radio system as a function of the ratio of the high data rate to the low data rate channels. The system studied is defined in Section 2, with zero capture receivers, a variable MNT scheme, and a HBH Ack based on the checksum at the end of the packet.

Four different systems defined by the ratios of 2 to 1, 4 to 1, 8 to 1, and 12 to 1, were considered. The systems were tested for offered rates ranging from 15% to 60%. The significant performance measures of throughput, average round trip delay, and average buffer occupancy, for all the runs are summarized in Table 4. Figures 23 to 26 compare the performance of the systems in terms of the above measures and the ratio of throughput to input rate, all as a function of the offered rate.

---

* The present experimental system uses 100 Kb/s and 400 Kb/s.

Apart from the buffer occupancy which does not show a definite trend to justify conclusions, all other measures of performance clearly demonstrate the following. An increase in the ratio from 2/1 to 4/1 significantly improves system performance. Similarly, an increase of the ratio from 4/1 to 8/1 also demonstrates a significant improvement in performance. On the other hand the performance of the system with the ratio 12/1 is almost the same as that of the system with the ratio 8/1, hence no significant improvement is observed in this range. For example, for an offered rate of 30%, the measured throughputs are 15.69%, 18.86%, 25.15%, and 26.29%, for the systems with ratios 2/1, 4/1, 8/1, and 12/1, respectively. Similarly, the measured average round trip delays for a load of 30% offered rate are 24.99, 21.37, 10.39, and 9.77 packet slots, for the systems with ratios 2/1, 4/1, 8/1, and 12/1, respectively.

Assuming that the low data rate channel is 100 Kb/s, this study demonstrates that the best choice for the high data rate channel will be between 400 Kb/s and 800 Kb/s. No significant gain is obtained when the data rate is increased beyond 800 Kb/s as is clearly demonstrated in Figures 23 through 26.

OFFERED RATE [%]	THROUGHPUT [%] RATIO OF DATA RATES				AVERAGE ROUND TRIP DELAY [SLOTS] RATIO OF DATA RATES				AVERAGE BUFFER OCCUPANCY [PACKETS] RATIO OF DATA RATES			
	2/1	4/1	8/1	12/1	2/1	4/1	8/1	12/1	2/1	4/1	8/1	12/1
15	10.15	13.09			12.03	7.91			5.18	2.75		
24	14.65	19.97	22.86	24.19	13.69	12.49	11.94	8.68	6.13	6.89	5.84	4.56
30	15.69	18.86	25.15	26.29	24.99	21.37	10.39	9.77	8.24	7.77	6.55	5.10
36	13.96	17.91	26.44	28.22	23.85	29.76	21.12	19.63	7.70	10.02	7.86	9.83
45			28.70	29.31			19.68	21.28			10.00	9.60
60			26.58	28.11			22.21	21.56			9.15	9.60

TABLE 4

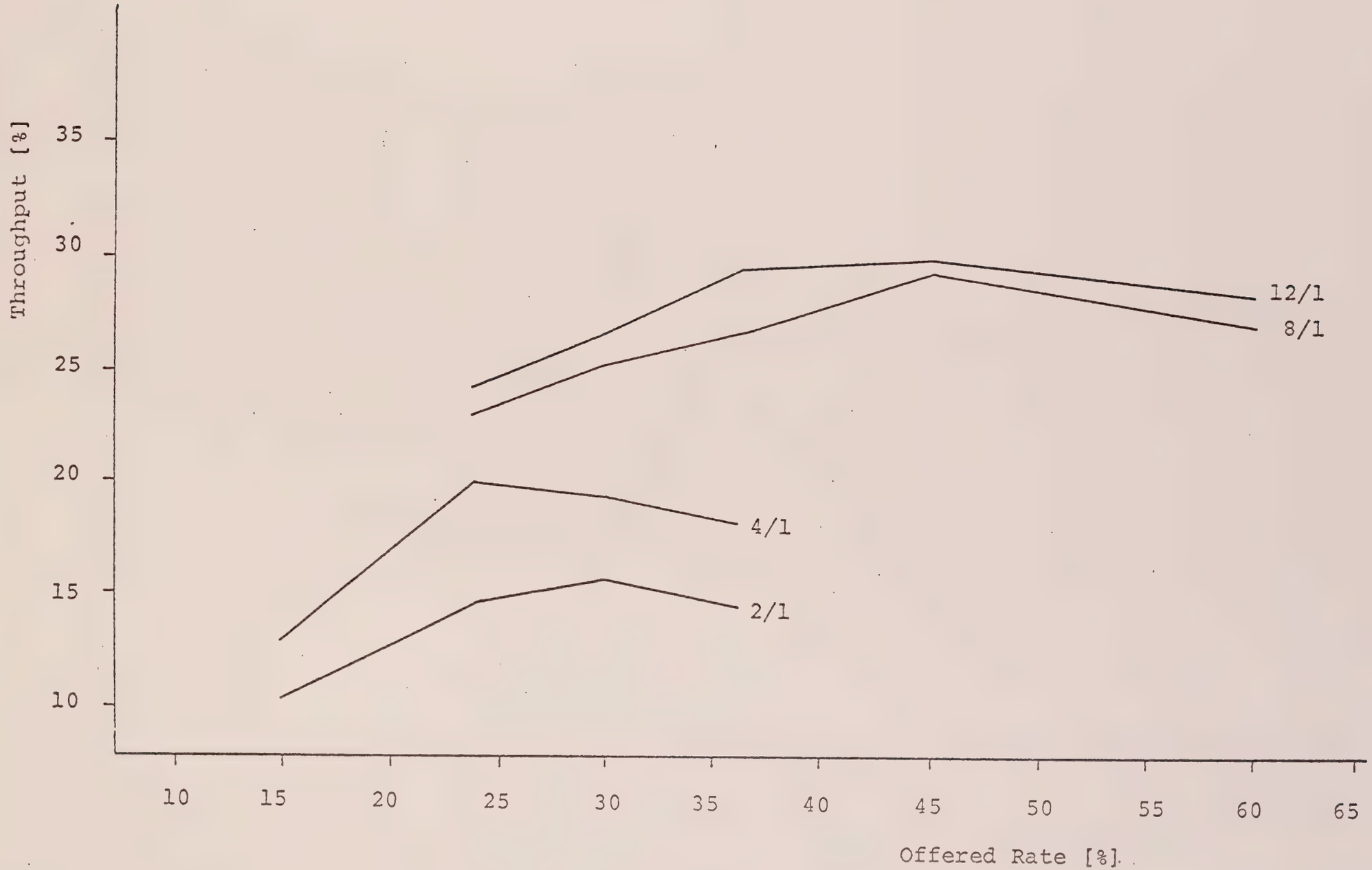

Throughput [%]
35
30
25
20
15
10
12/1
8/1
4/1
2/1
10
15
20
25
30
35
40
45
50
55
60
65
Offered Rate [%]

FIGURE 23

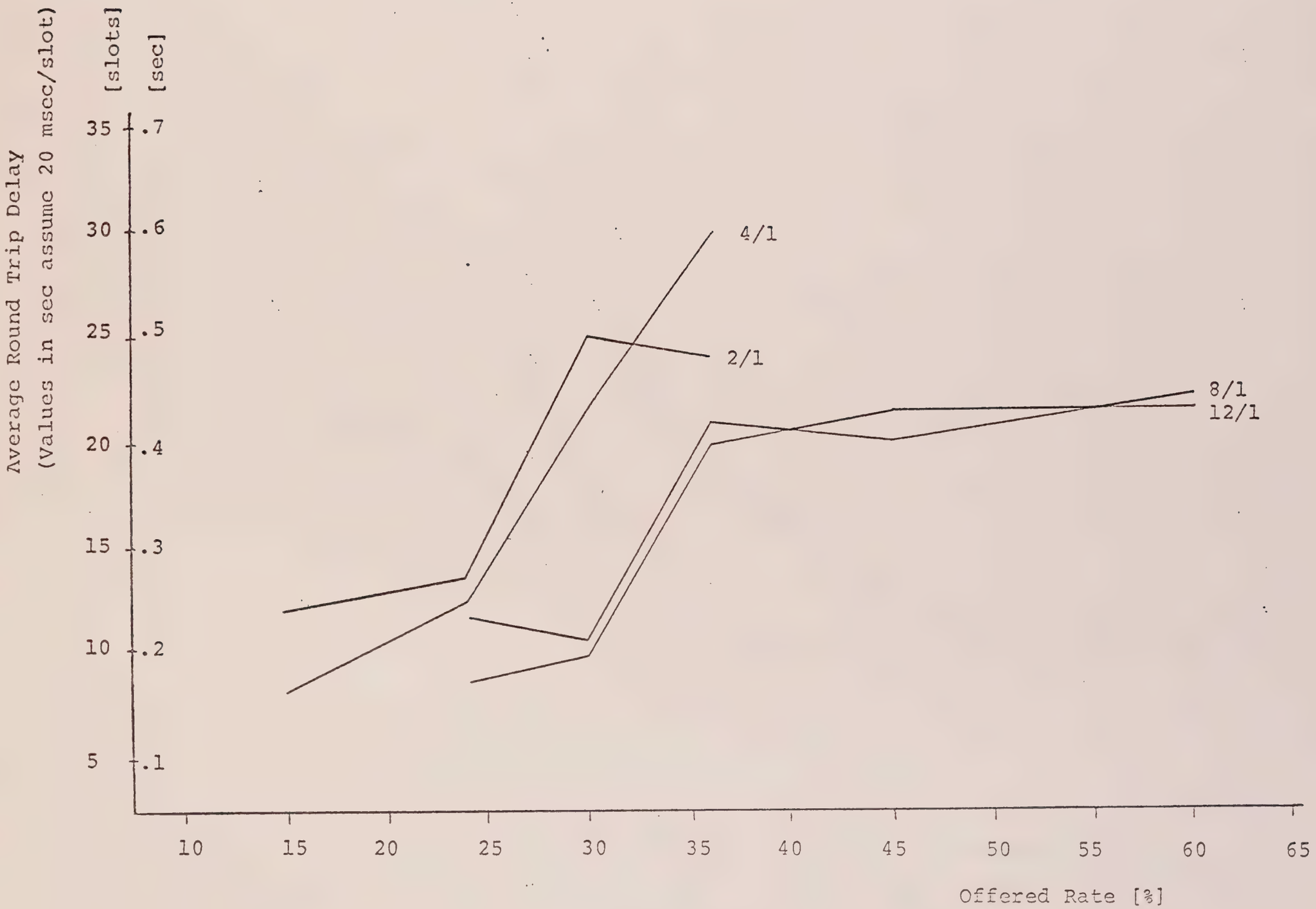

Average Round Trip Delay
(Values in sec assume 20 msec/slot)
[slots]
[sec]
35
30
25
20
15
10
5
.7
.6
.5
.4
.3
.2
.1
4/1
2/1
8/1
12/1
10
15
20
25
30
35
40
45
50
55
60
65
Offered Rate [%]

FIGURE 24

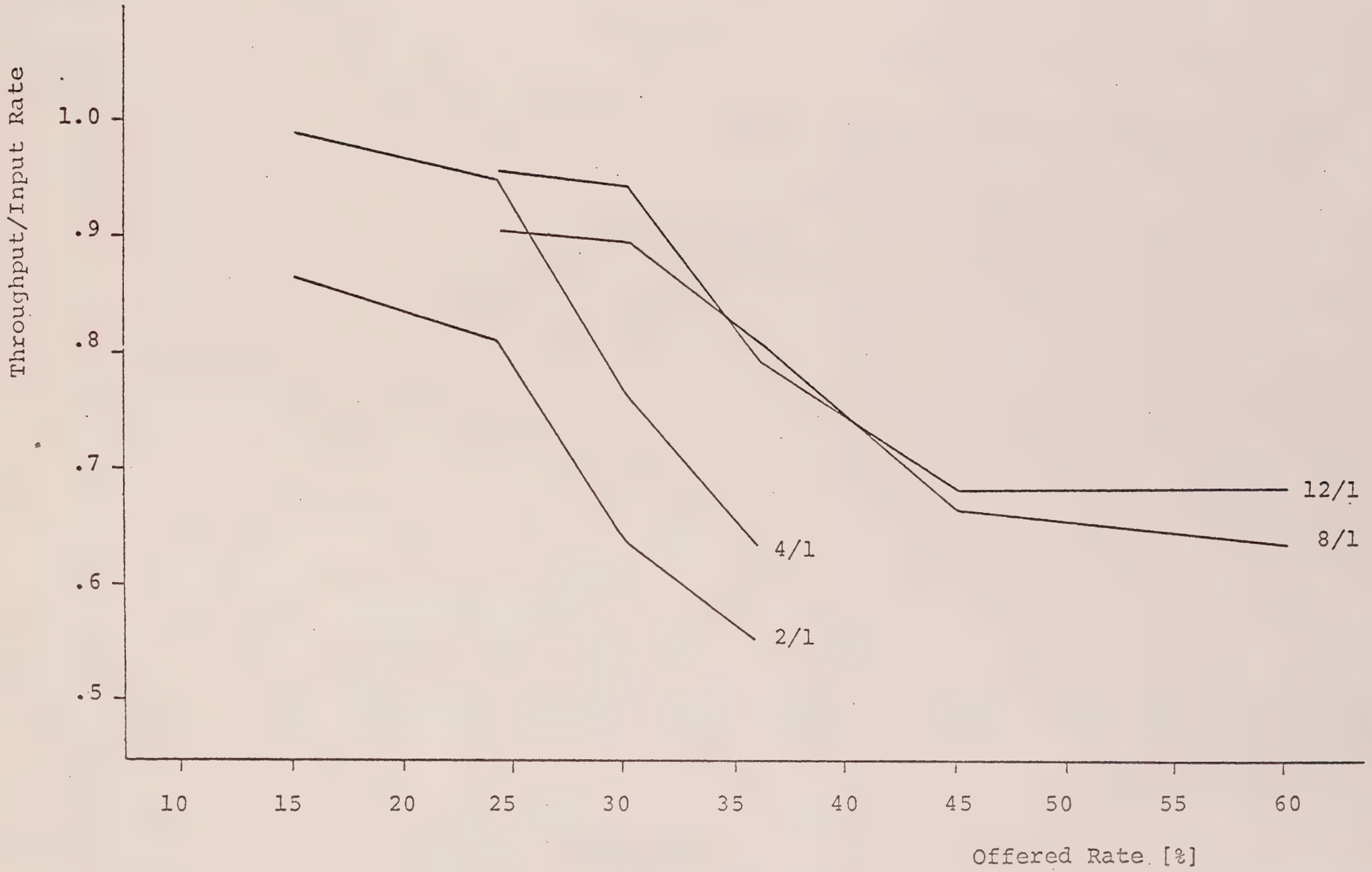

Throughput/Input Rate
1.0
.9
.8
.7
.6
.5
10
15
20
25
30
35
40
45
50
55
60
Offered Rate [%]
12/1
8/1
4/1
2/1

FIGURE 25

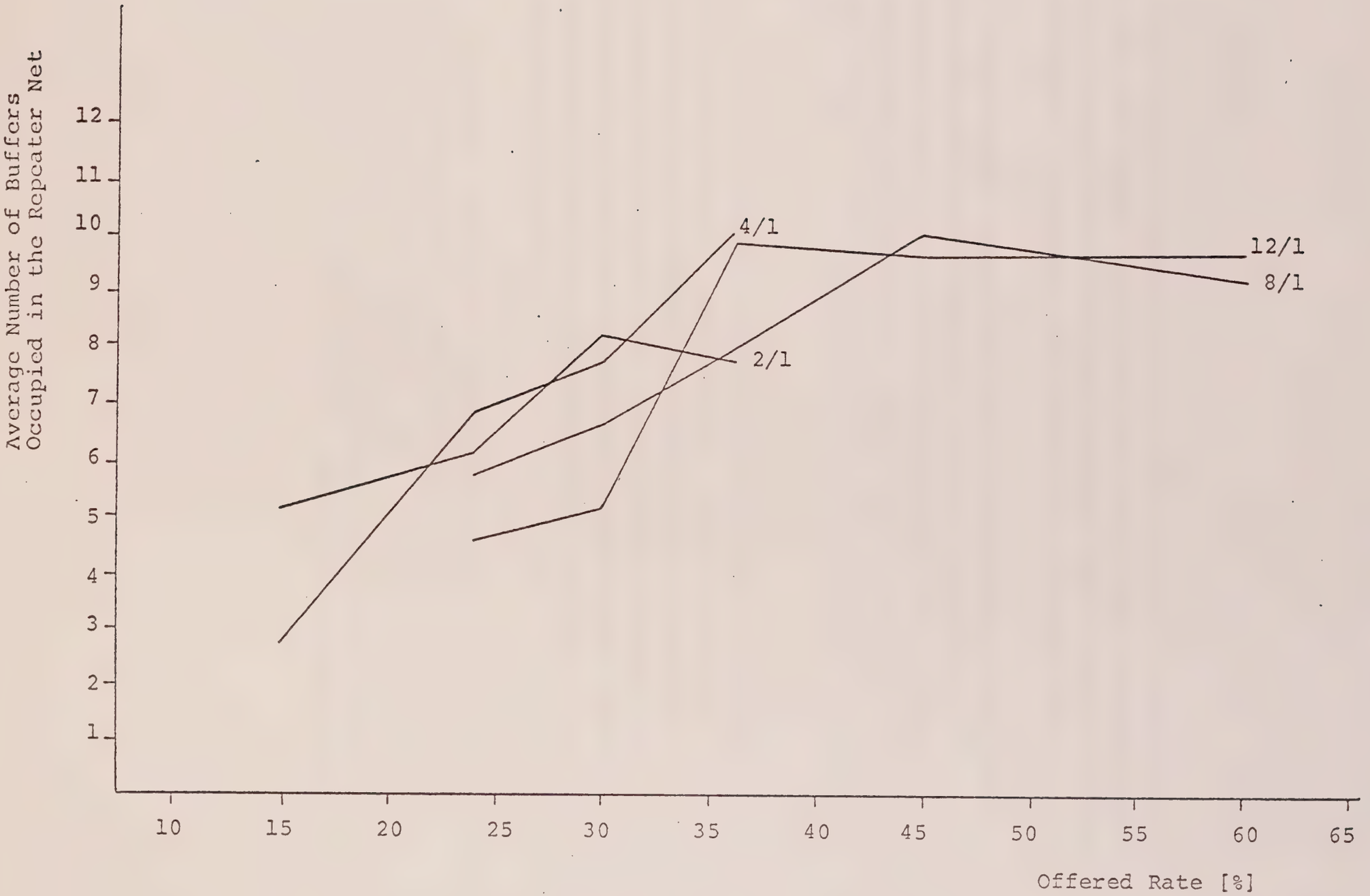

Average Number of Buffers
Occupied in the Repeater Net
12
11
10
9
8
7
6
5
4
3
2
1
4/1
12/1
8/1
2/1
10
15
20
25
30
35
40
45
50
55
60
65
Offered Rate [%]

FIGURE 26

7. CONCLUSIONS

Several specific design alternatives have been studied using a simulation approach. The alternative packet radio systems which result for a given design issue were compared on the basis of relative performance. The major conclusions of the study were:

1. The maximum number of packet transmissions, MNT, before discarding the packet should be software modifiable. A variable MNT as a function of the hierarchy level demonstrated the best performanc. When a fixed MNT is used, a small value of MNT between 3 and 6 is preferrable to large values.

2. A perfect capture receiver significantly improves system performance in two aspects. It increases the system capacity (maximum throughput) for a given value of delay, and it results in a system which is less sensitive to overload fluctuations by demonstrating gradual ("gracefull") degradation as compared to the system with zero capture receivers.

3. A system which uses a header checksum, utilized for HBH Ack, performs better than one which uses only a checksum at the end of the packet. The difference in performance depends upon the relative header and packet sizes as well as the fraction of short (header size) packets in the network.

4. For a given 100 Kb/s low data rate channel, it is demonstrated that the "optimum" value for the high data rate channel will be between 400 Kb/s and 800 Kb/s. No significant gain in system performance is obtained when the high data rate channel is increased beyond 800 Kb/s.

It is noted that all the studies of this chapter were done for a single station packet radio network. It is not anticipated that any of the conclusions of the studies presented in this chapter will change for multistation packet radio systems. However, it is noted that other design issues which are specific to multistation networks need to be studied.

REFERENCES

[ABRAMSON,70] Abramson, N., "The ALOHA System - Another Alternative For Computer Communication", 1970 Fall Joint Computer Conference, AFIPS, Conf. Proceedings, Vol. 37, pp. 281 - 285.

[FRANK, 75] Frank, H., I. Gitman, and R.M. Van Slyke, "Packet Radio System - Network Considerations", Proceedings of the National Computer Conference, May, 1975, pp. 217 - 231.

[GITMAN, 75] Gitman, I., R.M. Van Slyke, and H. Frank, "Routing in Packet Switching Broadcast Radio Networks", Submitted for publication.

[KLEINROCK, 75] Kleinrock, L., and F. Tobagi, "Random Access Techniques for Data Transmission Over Packet Switched Radio Channels", Proceedings of the National Computer Conference, May, 1975, pp. 187 - 201.

[NAC, 74] Network Analysis Corporation, "Simulation of Packet Switched Communication Networks", in The Practical Impact of Recent Computer Advances on the Analysis and Design of Large Scale Networks, Third Semiannual Technical Report, June 1974, available from Defense Communication Center, Arlington, Va.

REFERENCES Cont.

[NAC, 75a] Network Analysis Corporation, "Maximum Number of Transmissions For Packet Radio Repeaters and Stations", Packet Radio Temproary Note #153, available from ARPA Network Information Center, Stanford Research Institute, Melno Park, California.

[NAC, 75b] Network Analysis Corporation, "Comparison of Packet Radio Networks With Zero Capture and Perfect Capture Receivers", Packet Radio Temporary Note #154, available from ARPA Network Information Center, Stanford Research Institute, Melno Park, California